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Impact of climate extremes on wildlife plant flowering over Germany

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Abstract

Ongoing climate change is known to cause an increase in the frequency and amplitude of local temperature and precipitation extremes in many regions of the Earth. While gradual changes in the climatological conditions are known to strongly influence plant flowering dates, the question arises if and how extremes specifically impact the timing of this important phenological phase. In this study, we systematically quantify simultaneities between meteorological extremes and the timing of flowering of four shrub species across Germany by means of event coincidence analysis, a novel statistical tool that allows assessing whether or not two types of events exhibit similar sequences of occurrences. Our systematic investigation supports previous findings of experimental studies by highlighting the impact of early spring temperatures on the flowering of wildlife plants. In addition, we find statistically significant indications for some long-term relations reaching back to the previous year.

1 Introduction

In comparison to geological time-scales, ongoing climate change is extraordinarily fast (IPCC, 2013). The associated changes in meteorological conditions, which are among the main driving factors for plant growth, are a huge challenge for ecosystem resilience. For some ecosystems the quick changes may even exceed their ability to adapt to the new conditions, leading to severe ecological disturbances.

Beyond the gradual change of mean climatology, also the spatial extent, intensity, and frequency of extreme climate events like droughts, heat waves or storms have markedly increased over the past decades (Horton et al., 2001; IPCC, 2013). Both, the probability of occurrence and the amplitude of many types of climatic extremes have been rising (Fischer et al., 2007; Barriopedro et al., 2011; Petoukhov et al., 2013) and are projected to further increase (Stott et al., 2004; Rahmstorf and Coumou, 2011; Petoukhov et al., 2013). Especially during recent years, extreme summer temperatures have been observed which were clearly beyond the limits of previously observed extreme values. Specifically, examples like the European heat wave in 2003 (Schaer et al., 2004; Luterbacher et al., 2004; Garcia-Herrera et al., 2010) or the Russian heat wave in 2010 (Trenberth and Fasullo, 2012) exceeded historical extreme values of the past 500 years by far and, thus, quantitatively changed the known probability distribution of extreme climate events (Barriopedro et al., 2011). A multitude of possible explanations for this development has been proposed, including a positive temperature-soil moisture feedback (Fischer et al., 2007) or the enhancement of frequency and persistence of specific large-scale circulation patterns by a quasi-resonant amplification of planetary waves (Petoukhov et al., 2013). For the mid-21st century, another up to tenfold increase of the probability of the occurrence of a heat wave similar to that of 2010 over Europe has been projected (Barriopedro et al., 2011).

While past and ongoing trends of heavy rainfall events strongly depend on region and season (Klein Tank and Konnen, 2003; Bartholy and Pongracz, 2007; Lupikasza et al., 2011), future projections suggest increases of those events' frequency and intensity for most parts of Europe (Kundzewicz et al., 2006; Kysely et al., 2011; Rajczak et al., 2013).

The effects of climate extremes on terrestrial ecosystems are diverse, highly complex and may lead to unprecedented outcomes. Besides the possible feedback enhancement of global warming by the reduction of terrestrial carbon uptake (Babst et al., 2012; Reichstein et al., 2013; Zscheischler et al., 2013), climate extremes can lead to a sustained perturbation or even destruction of terrestrial ecosystems, which has been observed for semi-arid regions (Allen and Breshears, 1998; Fernandez et al., 2014; Miranda et al., 2014) as well as for alpine ecosystems (Galvagno et al., 2013; Arnold et al., 2014). Due to the combination of a higher temperature variability during spring months with a generally earlier start of the growing season, the vulnerability of central European temperate forests to climate extremes is increasing as well (Menzel and Fabian, 1999; Root et al., 2003; Walther, 2004).

Beyond the aforementioned direct impacts, there is a growing body of evidence that climate extremes can critically disturb sensitive ecological equilibria (Parmesan, 2006) and mutualisms (Rafferty et al., 2015). The effects of temporal displacement or even absolute failure of flowering and fruit ripening of food plants on nectarivores, small mammals and birds is one important example (Law et al., 2000; Jacobs et al., 2009). Rapid population decline up to species extinction due to phenological mismatches between plant and pollinator has already been demonstrated (McKinney et al., 2012; Burkle et al., 2013; Kudo and Ida, 2013). The resulting damage on the affected population could propagate through the ecosystem and endanger its structure, stability and dynamics (Post and Stenseth, 1999; Parmesan et al., 2000; Parmesan, 2006; Augspurger, 2009).

A widely used source of data allowing to study the inter-annual variability of plant growth dynamics is the timing of phenological phases. From several studies, it is known that the phenological phases of most central European plant species experience systematic, gradual changes related to climate change. Especially the change in temperature seems to play an important role for long-term variations in the dates of foliation, flowering and leaf coloring (Ahas et al., 2000; Sparks et al., 2000; Sparks and Menzel, 2002; Menzel, 2003; Cleland et al., 2007; Schleip et al., 2012).

However, it is likely that seasonal extreme temperatures can affect terrestrial ecosystems much stronger and more directly than gradual changes (Easterling et al., 2000; Jentsch et al., 2007, 2009; Zimmermann et al., 2009; Menzel et al., 2011; Nagy et al., 2013; Reyer et al., 2013). Associated with extreme weather conditions, flowering dates of temperate species have been observed to be shifted by up to one month or to have even failed completely (Nagy et al., 2013).

Unlike for temperature extremes, there is an ongoing debate concerning the impact of drought or heavy precipitation events on plant flowering. So far, only few studies have explicitly addressed this question, and those that have, are of experimental nature only. The experiments of Nagy et al. (2013) and Jentsch et al. (2009) found significantly delayed flowering dates of *Genistra tinctoria* after drought treatment. On the other hand, in the same study Nagy et al. (2013) found that the average flowering date of *Calluna vulgaris* was not significantly affected by drought. In the same spirit, Prieto et al. (2008) also found no shift in flowering of *Erica multiflora* related to drought. Heavy rainfall did not effect flowering time at all in both experiments of Nagy et al. (2013) and Jentsch et al. (2009).

In general, the reaction of flowering to climate extremes has so far mainly been analyzed for individual events (Luterbacher et al., 2007; Rutishauser et al., 2008) or with experimental setups (Prieto et al., 2008; Jentsch et al., 2009; Nagy et al., 2013). Systematic studies exploiting existing large-scale spatially distributed data on phenological phases by means of sophisticated data analysis methods are rare. As one notable exception, Menzel et al. (2011) presented an in-depth analysis of the influence of warm and cold spells on crop plant phenology over Europe. However, since agricultural crops are often subject to specific treatments (which has changed over the past decades), these results are not directly transferable to wildlife plants, for which a corresponding study is still missing.

In order to close this research gap, in this work we investigate the individual influence of extremely high and low temperature and precipitation events (but not their combined effect in terms of droughts, since the appropriate definition of the latter presents a problem on its own that is beyond the scope of this work) on the flowering dates of some German wildlife plant species, using a phenological data set covering the time span of 1950–2010. In contrast to other recent studies (e.g., Rybski et al., 2011), we intentionally focus on flowering as a single phenological phase with paramount ecological importance. Moreover, we select four of the most abundant German shrub species (see Sect. 2) as a case study to address the following research questions:

- do the flowering dates of wildlife shrub species systematically react to temperature and/or precipitation extremes?
- Which species are more/less susceptible?
- Do these effects differ by region?

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The remainder of this paper is organized as follows: After a description of the phenological and meteorological data sets under investigation, the approaches of extreme value definition as well as the methodology of event coincidence analysis are described in Sects. 2 and 3, respectively. Subsequently, the results of our study are presented in Sect. 4 and discussed accordingly in Sect. 5. We conclude this paper with a short summary of the results in Sect. 6.

2 Data

2.1 Meteorological data

As a climatological reference data set, we use an ensemble of homogenized and expanded daily mean temperature and precipitation time series from Österle et al. (2006), which are based on meteorological stations operated by the German Weather Service (DWD) (Deutscher Wetterdienst, Offenbach, 2009). While the precipitation data is directly based on observations made at all considered stations, mean temperatures partially involve a sophisticated spatial interpolation from a set of fewer stations with direct measurements (Österle et al., 2006). Both data sets are commonly employed as a benchmark data set for assessing the performance of hindcast simulations of regional climate models (German baseline scenario). The data covers the time interval from 1950 to 2010 and comprises 1440 records distributed over Germany as well as a set of stations located in the adjacent regions of some of its neighboring countries.

2.2 Phenological data

As a source of information on the reactions of terrestrial ecosystems to climatic drivers, we use the German Plant Phenology Data Set, provided by DWD (http://www.dwd.de/phaenologie). This data set contains the Julian days of the occurrence of several phenological phases. Besides 22 fruit species and 22 crop types, the data covers 37 wildlife species at 6525 stations distributed over all of Germany for a time span from 1951 to 2013. However, the actually available time series length strongly varies by station. While some stations have series covering the full considered time period, others contain just a few or even only one observation per plant species and phenological phase. Due to these different time series lengths, we select only those stations for our further analyzes, which contain at least 40 years of observation between 1951 and 2010.

In this work, we analyze flowering dates of four wildlife shrub species that are widely spread over Germany: Lilac (*Syringa vulgaris L.*), Elder (*Sambucus nigra L.*), Hawthorn (*Crataegus monogyna Jacq. / Crataegus laevigata (Poir.) D. C.*) and Blackthorn (*Prunus spinosa L.*). These four shrubs are characterized by a usually large amount of flowers during early to late spring. All four species are important components of their local ecosystems and in some regions key for local insect, bird or small mammal populations. Hawthorn and Blackthorn, for example, are being visited by 149 and 109 insect species, respectively, with around 100 lepidoptera species among them (Southwood, 1961). In contrast, Elder is of lower importance for insect species (only around 20 species are known to depend on Elder flowers or fruits, see Duffey et al., 1974), but is an important food source for numerous birds during summer and autumn due to its high amount of very nutritious berries (Atkinson and Atkinson, 2002).

The mean flowering times of the four shrub species range from early April (Blackthorn) over May (Hawthorn and Lilac) to mid-June (Elder), see Fig. 1. The distributions of flowering dates of all four species are, however, very wide. Flowering can even occur 1–2 months earlier than normal under certain conditions, which shall be further explored during the course of this work. Due to the selection criterion of 40 years of data (at most 20 missing years of observations), the data set is strongly reduced to about 1000 records per plant, and the spatial distribution of the corresponding phenological stations becomes much more heterogeneous, with larger gaps existing especially for Blackthorn in Northeastern Germany (Fig. 1).

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3 Methodology

3.1 Definition of extreme values

3.1.1 Phenology

In order to take a sufficiently large set of events into account that allows to draw statistically justified conclusions, we define a flowering date earlier than the 10th percentile of each single phenology time series to be extreme. Hence, every phenological station has an individual absolute threshold date for the definition of such an event. This approach is important as it can be expected that the timings of the phenological phases of every station crucially depend on local conditions like altitude, exposition, water availability, etc. The explicit study of the corresponding effects is, however, beyond the scope of the present work. Since the time series lengths differ between the different phenological records (40 to 61 observations), this approach also leads to a different number of extremes for each time series. The definition of extreme late flowering dates is performed in full analogy using the 90th percentile.

3.1.2 Temperature and precipitation

In order to obtain information on temperature and precipitation extremes that is directly comparable with the phenological information, a three-step treatment of the available continuous daily meteorological records is necessary, which is detailed below:

1. *Spatial interpolation:* As a first step, for each phenological station used in this study, we create one daily mean temperature (precipitation) series by spatial interpolation of the existing observational records. For this purpose, we apply a weighted mean interpolation, using the four closest meteorological stations surrounding a phenological station. Since we are only interested in the timing of (local and seasonal) temperature (precipitation) extremes rather than the associated explicit values of the respective variables, we do not explicitly take other covariates

like altitude into account, although being aware of their actual relevance for the timing of flowering. Due to the different spatial coverage of phenological data for the four considered plant species, this approach results in four new temperature (precipitation) data sets to be further exploited as described in the following.

2. *Temporal averaging:* Extreme climatic conditions present for just a single day may not be sufficient to remarkably trigger an ecological response like the date of flowering (Menzel et al., 2011). In turn, given the common time-scales of plant physiological processes, it appears reasonable to consider extremes in the mean climate conditions taken over a certain period of time. The aspect of the crucial temporal duration of a climatic extreme event to influence flowering time is of special interest for the interpretation of the impact of climate change scenarios on plant flowering. Accordingly, in a second step of preprocessing, we calculate the average daily mean temperature (daily precipitation) for running windows in time. In order to study the effect of the averaging time-scale explicitly and potentially demonstrate the robustness of the obtained results against the specific choice of windows, we consider three different window sizes of 15, 30 and 60 days. These windows are moved along the time series with a step size of one day. For the 15 and 30 days periods, these windows start at 1 January of the year previous to the flowering and extend up to 1 December of the subsequent year (700 steps). For the 60 days window, the last step starts at 1 November (670 steps). This procedure leads to "window-mean temperatures (precipitation)", resulting in 700 (670) values for each year from 1951–2010 and for each phenological station. Notably, we use an unweighted averaging, giving the same weight to all observations within a given time window. The alternative approach of giving larger weights to observations close to the end of each window is not further considered here.

3. *Definition of temperature/precipitation extremes:* Before defining extreme window-mean temperatures (precipitation), we account for the numerous missing data values of the phenological data set by discarding the meteorological information

for all those years, where the corresponding phenological information is missing. We then identify those windows exceeding the 90th percentile (or falling below the 10th percentile, respectively) of all windows of the same size and time period at one station and consider them as extremes. By using this approach, the seasonal variability of temperature and precipitation is already included in the threshold definition, so that no further preprocessing (e.g., calculation of climatological anomalies or ’z scores’) is necessary.

3.2 Event coincidence analysis

To detect and quantify a possible statistical interrelationship between extreme seasonal temperatures (or extreme precipitation) and extreme flowering dates, we apply event coincidence analysis (Donges et al., 2011, 2015; Rammig et al., 2015), a novel statistical framework which allows identifying non-random simultaneous occurrences of events in two series. For this purpose, for each considered phenological station we convert the two time series (window-mean temperature/precipitation and flowering date) into binary vectors, representing time steps with or without such extreme conditions as explained above (see Fig. 2 for a schematic illustration of the approach). Subsequently, we count the number K_{obs} of simultaneous events (in the following referred to as “coincidences”).

Under the assumption of mutually independent events and, hence, independent exponentially distributed waiting times between subsequent events, the probability that exactly K coincidences are observed just by chance can be expressed as (Donges et al., 2011)

$$P(K) = \binom{N}{K} \left[1 - \left(1 - \frac{1}{T}\right)^{M}\right]^{K} \cdot \left[\left(1 - \frac{1}{T}\right)^{M}\right]^{N-K}. \qquad (1)$$

In the present case, N and M denote the number of extreme events in temperature/precipitation (N) and phenology (M) (here, $N = M$ by definition) and T the length of the time series (number of years of observation). Note that Eq. (1) takes the discrete nature of time steps in the phenological records (one year) into account and requires the sparseness of events, a criterion met by the definition of our event thresholds.

Equation (1) allows defining a simple significance test for the observed number of coincidences (K_{obs}) in two paired event series. For this purpose, we consider pairs of event series with

$$\sum_{K \geq K_{\mathrm{obs}}} P(K) < \alpha \tag{2}$$

with $\alpha = 0.05$ ($\alpha = 0.01$) to coincide significantly (i.e., non-randomly) at 5 % (1 %) confidence level. In this study the results are presented for two different α levels on the one hand, in order to demonstrate the sensitivity of the method to the choice of the significance level, and in turn to underline the robustness of possible results against the choice of the significance level.

By performing event coincidence analysis between flowering time and window-mean temperature/precipitation for different time windows before the typical flowering date, we can take possible lagged responses into account. In turn, the calculation of coincidence rates (i.e., relative fractions of coincidences) for, e.g., flowering dates and future temperatures that cannot causally be linked to the flowering, provides a simple yet powerful test of the reliability and robustness of the method.

We emphasize that under general conditions, there are two basic modes to perform event coincidence analysis (Donges et al., 2015): a “precursor test” (studying the appearance of a preceding climate extreme conditional on that of an extreme flowering date) and a “trigger test” (conditioning the timing of extreme flowering dates on previous extreme climatic events). Since we consider only climatic events at fixed points (windows) in time (instead of allowing for their appearance within a certain period potentially covering several subsequent windows) and have $N = M$, both tests are equivalent in the setting used in this study.

In comparison to classical correlation analysis as the statistical approach widely used in previous studies, event coincidence analysis only takes into account the (extreme) events obtained in the two time series, while for correlation all parts of the distributions of the variables are analyzed. Therefore, high (significant) coincidence rates mean “significantly simultaneous (extreme) events in two time series” while high (significant) correlation coefficients mean “significant general accordance between simultaneously observed values of the time series”. Theoretically, two strongly correlated time series can show a low coincidence rate for extreme events and vice versa. Moreover, we emphasize that correlation analysis only captures linear interrelationships between two observables, whereas this restriction is relieved in the case of event coincidence analysis.

4 Results

4.1 Coincidences with positive temperature extremes

We start our investigations considering Lilac as an example for illustrating the performance of our method in practice. Figure 3 demonstrates the existence of significant coincidences between very early Lilac flowering and extremely warm window-mean temperatures for three different window sizes and all windows from 1 January of the preceding year to 1 December of the year of flowering. Significant coincidences with $\alpha = 0.05$ are displayed in red, those that are also significant at $\alpha = 0.01$ in black.

For all three window sizes, a maximum number of significant coincidences is found during the spring months, especially around March and April. For time windows after the typical flowering time in May, there are generally much fewer indications for corresponding interrelationships than for windows before May. Note that due to the statistical nature of the employed analysis methodology, there are always individual stations exhibiting a significant number of coincidences just by chance, even if there cannot be a causal link between the considered events. However, at a 5 % confidence level, we may expect that at most 5 % of the stations show such false positive results (same at

1 % level), which is about the order of the maximum numbers of stations with significantly many coincidences observed after May. Hence, this behavior is to be expected.

Regarding the latitudinal distribution of stations with significant coincidences, we do not observe any systematic trend with one exception: at the northernmost stations, the timing of significant coincidences between early flowering and extreme positive temperature anomalies tends to extend further into the late winter than for the more southern stations.

Considering time windows from the previous year, we find some indications for summer (60 days windows) and autumn (15 and 60 days windows) temperature extremes to significantly coincide with early flowering in more cases than to be expected by the tolerable number of false positives in our testing procedure (Fig. 3). This effect is mainly present at the more northern stations. We will further discuss possible explanations of these findings in Sect. 5.

Following upon the previous findings for Lilac, Fig. 4 summarizes the corresponding results for the flowering of the other three species (red lines). For convenience, we only show the results for two window sizes and no latitudinal resolution. For Elder the maximum fraction of stations with significant coincidences arises (due to the generally later flowering of Elder) between March and May. Later windows also show a few stations with significant coincidences due to the previously discussed test design. A clear latitudinal gradient is absent in the significance profile (not shown). As an exception, for the windows between January and March with a window size of 60 days, again mainly the more northern stations show significant coincidences, exhibiting 1–2 peaks in the corresponding temporal profile around the previous year's May and September. The latter peak is especially pronounced for the 15 days windows.

The results for Hawthorn closely resemble those obtained for Elder, including a clear maximum in the fraction of stations with significant coincidences in late spring and no clear influence of latitude. However, the corresponding signal during May and September of the preceding year is less pronounced or not even visible at all. Only for 15 days windows, there are again significant coincidences with September temperatures at the northern stations clearly beyond the expected number of false positives.

Finally, the results for Blacktorn are markedly shifted towards early spring, consistent with the generally earlier flowering of Blackthorn in comparison to the three other shrub species. In contrast, the pertaining signal in the previous autumn is distinctively stronger in the 30 days window than for the other species.

4.2 Coincidences with negative temperature extremes

The blue lines in Fig. 4 display the results of the event coincidence analysis between negative (cold) temperature extremes and late flowering. The general shape and intensity of the temporal profile of the number of stations with significant coincidences are similar to the results reported above for extremely positive seasonal temperature anomalies, yet slightly shifted towards later time windows. Most results do not show any significant peaks of the number of stations with statistically significant coincidences in the previous year, with the exception of Blackthorn, where even more distinct peaks in the previous year can be seen than for positive temperature extremes (at least for small windows). Likewise, the tendency of coincidences with temperature extremes in the previous year to be more pronounced at more northern latitudes (as observed for warm extremes) is not visible at all within the results for cold temperatures (not shown). In turn, there is even an opposite tendency: for Blackthorn, peaks in the previous year almost completely result from stations south of 50° N.

4.3 Coincidences with precipitation extremes

As described in the Sect. 1, the impact of heavy or low rainfall amounts on flowering date is a controversial topic. To contribute to this ongoing debate, we performed event coincidence analysis between extremely high/low precipitation amounts and extremely early/late flowering. For all four shrub species and all four possible extreme event combinations, we hardly ever find more than 5 % of the stations showing significant coincidences. Only two small exceptions were observed for Blackthorn, but these are probably a result of the fact that very warm spring conditions normally result from intense westerly circulation patterns, which are characterized by relatively high precipitation amounts in Central Europe. We thus conclude that there is no significant indication of a marked impact of precipitation extremes on the flowering of the four considered shrub species over Germany. Note that the productivity of German terrestrial ecosystems is commonly not limited by water availability. Hence, this result does not necessarily imply a similar absence of relationships for other species and/or regions, especially in situations where water stress can be a problem. We plan to further address this question in our future work.

4.4 Spatial distribution of significant coincidences with positive temperature extremes

As discussed above, we have found significant coincidences especially between early flowering and positive temperature extremes. Specifically, the former analyzes revealed two time intervals of particular interest: late winter / early spring and the previous year's early to mid-autumn. In the following, we will examine the spatial distribution of records with significantly coincident extremes for both time windows.

Figures 5 and 6 show maps with the corresponding results. In order to condensate the potentially large amount of information provided by this analysis, we only plot two maps per plant species representing the two different time intervals. Black (red) signatures mark those stations, which show at least one window with significant coincidences at $\alpha = 0.01$ ($\alpha = 0.05$) significance level within the time intervals marked by dashed lines in Fig. 4. The obtained results allow not only studying the latitudinal distribution of significant coincidences as shown in Fig. 3, but also possible patterns or regional clustering of significant results. However, for the 30 days period in spring (Fig. 5), neither a clear pattern nor geographical clusters of stations with significant coincidences are visible. The obtained spatial pattern seems not to depend markedly on altitude, continentality or landscape type, but an in-depth study of possible statistically significant dependencies on corresponding covariates is beyond the scope of this work.

In contrast to the latter findings, at least the maps for Lilac and Hawthorn in Fig. 6 show a weak tendency towards a spatial accumulation of stations with significant coincidences in Northern Germany. In turn, the signatures for Blackthorn concentrate more in the southern part of Germany. However, this observation could also be an artifact of the missing data for most of Northeastern Germany.

5 Discussion

The results displayed in Figs. 3 and 4 demonstrated that event coincidence analysis (in combination with a sliding window approach) is an appropriate technique to identify periods during or prior to the growing season, where extreme temperatures or precipitation sums are statistically related with extreme flowering dates. To our best knowledge, no similar analysis has been performed so far. In turn, all previous studies on possible relations between climate variables and flowering times have been based on linear correlation (Ahas et al., 2000; Sparks et al., 2000; Menzel, 2003). While correlations take all parts of the distributions of the two considered observables into account, event coincidence analysis exclusively focuses on the extremes, ignoring all other values. Although it was already known that early spring temperatures are strongly influencing flowering dates, the specific validity of such a relationship for extreme values cannot be concluded from classical correlation analysis. Our methodological approach showed that the relationship indeed also applies to the extreme values of temperature and flowering time.

In order to compare the respective results of event coincidence analysis and correlation analysis concerning the overall strength of interdependence between temperature and flowering time, Fig. 7 shows two selected examples taken from Fig. 4 (Lilac flowering, 30 days window size) together with the corresponding results of a classical linear correlation analysis of the explicit data values and a correlation analysis based on the binary (event) data. Note that the significance tests used for coincidence analysis and correlation analysis conceptually differ so that the obtained numbers of stations with significant relationships between climate and ecosystem dynamics should not be compared quantitatively. In particular, the test used for event coincidence analysis is based on the assumption that the events in the two studied series can be described by independent Poisson processes, and hence calculates the probability of the observed number of coincidences to occur in two random data sets. In contrast, the significance of the correlation values for each station is assessed in terms of a classical t test.

Although a direct quantitative comparison between the results of the three different analysis methods is not possible, we find that the time period with the highest number of stations with significant relationships is similar for both coincidence and correlation analysis. In turn, the computation of correlation values based upon binary event data does not produce meaningful results, which is to be expected since the binary data differ markedly from a normal distribution (or at least sufficiently continuous distribution) implicitly assumed when applying correlation analysis. As a result, the number of stations with apparently significant correlations between the binarized variables is extremely high (beyond the expected false positive rate) even for time windows after the flowering event, for which the latter cannot be causally linked to climatic variations. The comparison of these three approaches thus highlights the added value of event coincidence analysis for event-based environmental research. Figure 7 additionally demonstrates, that the non-causal false positive signatures after the date of the flowering are markedly reduced, whereas corresponding significant cross-correlations tend to remain at a relatively large subset of stations. In general, event coincidence analysis highlights a distinctively lower set of time periods during which the climatic conditions are directly related with the timing of flowering.

Another notable observation of this study is that positive temperature extremes (warm periods) that coincide with early flowering do not occur arbitrarily early in the year. This general finding is valid for all four analyzed shrub species. However, an important exception can be seen at some stations in the very north of the study region and thus close to the North and Baltic Sea. For these stations, the time windows for which significant coincidences between temperature and flowering date are evident, reach much further into late winter. This observation could result from the regulating effect of these two large water bodies, the large heat capacity of which allows maintaining relatively warm but not necessarily extreme air temperatures (especially during night time, i.e., suppressing freezing conditions during winter time) for a considerable period of time. As a consequence, an extremely warm period in, for example, January can have a persistent effect on terrestrial ecosystems in coastal regions over the following weeks, resulting in coincidences between positive January window-mean temperature extremes and early flowering. This effect also explains why the prolonged significance peaks (late winter until late spring) of the northernmost stations in Fig. 3 are mainly visible for the longer time windows, since only long-lasting unusally warm conditions are stored for a markable amount of time. A similar time-lagged regulatory effect of large water bodies on air temperatures (mediated via the long-term memory of sea-surface temperatures) is well known for El Niño events (Kumar and Hoerling, 2003). It was also found that North Atlantic temperature anomalies can influence atmospheric conditions in the following seasons with time lags up to several months (Wedgbrow et al., 2002; Iwi et al., 2006). However, we are not aware of any documented evidence for such a delayed ecosystem response reported so far.

Our analysis also reveals another important observation: For Lilac, Elder, Hawthorn and Blackthorn (Fig. 3), we find a small but noticeable signature of coincidences between very warm 15 days windows during early September and very early flowering in the following year. Both features are relatively weakly expressed in comparison to the spring temperature anomalies directly preceding the flowering, but still far larger than the expected tolerable false positive rate of our test setting as exemplified by a few obviously non-causal coincidences with time windows after the flowering event. Indications for the existence of such significant statistical relationships between flowering and temperatures of the previous growing season have already been reported by, e.g., Sparks et al. (2000) for Autumn Crocus, and by Fitter et al. (1995); Luterbacher

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et al. (2007) and Crimmins et al. (2010) for various other plant species. The direction of the influence of warm autumn temperatures on the timing of flowering thereby seems to strongly depend on plant species and geographical conditions like elevation (Crimmins et al., 2010). However, based upon our analysis we cannot yet fully rule out that the corresponding findings of this study are statistical artifacts resulting from the auto-correlation of temperature time series. For example, it could be possible that in all those years during which the September was unusually warm, the following spring was very warm as well. An argument against this explanation is that the timing of the autumn signal is clearly later for Blackthorn, although the same temperature data was used. In order to further address this question, future studies should explicitly address the potential influence of auto-correlations in more detail, calling for a methodological extension of event coincidence analysis conditioning on previous events (in a similar spirit as partial correlations or conditional mutual information, see e.g. Balasis et al., 2013).

A potential drawback of the used approach of event coincidence analysis for non-binary data could be the potential dependence of the results on the threshold used for the definition of an extreme. In this study, we used the 90th and 10th percentiles for temperature, precipitation and flowering time, respectively. In order to further demonstrate the robustness of our results, Fig. 8 recalls the results of Fig. 4 (right panel, second row) with five different threshold definitions. The obtained results show that although the absolute number of stations with significant coincidences varies among the different threshold combinations (as is expected from the definitions of events and coincidences), the general temporal profile qualitatively remains the same for most windows. Specifically, in most cases the obtained numbers of stations with significant coincidences are larger for less restrictive thresholds. As a notable exception, regarding the relevance of warm autumn temperature in the previous year, we find an opposite behavior, i.e., the event coincidence analysis using a more restrictive threshold (green line in Fig. 8) results in a higher number of significant stations than the same analysis employing more conservative thresholds (e.g., red line in Fig. 8). Hence, whereas the relationship between extremely positive temperature anomalies in spring and early flowering appears to consistently apply for different event magnitudes, for the previous autumn, the strongest positive anomalies have an over-proportional relevance for the emergence of very early Elder flowering.

6 Conclusions

In summary, the first-time application of the modern statistical concept of event coincidence analysis to phenological data revealed a clear statistical relationship between extremely warm temperatures in spring and extremely early flowering dates of Lilac, Elder, Hawthorn and Blackthorn, as well as between extremely cold temperatures in spring and extremely late flowering dates. Although this relationship is not evident for all German stations, the coincidences are quite homogeneously distributed over the study area. In addition to the expected relevance of spring temperatures, we identified a period during the previous year's autumn, where extremely warm temperatures significantly coincide with an extremely early flowering in the subsequent year. Although the signatures of this period are not very strong, they are clearly visible. Our study revealed that this effect becomes even stronger when more restrictive threshold definitions are used. In contrast to the confirmed dependence of early and late flowering events on temperature extremes, our analysis did not identify similar marked statistical relationships between extreme precipitation amounts and the timing of flowering.

To answer the research questions formulated in the introduction, we conclude that extremely high (low) temperatures do significantly coincide with extremely early (late) flowering, especially if the extreme period appears during early spring. All four analyzed shrub species show the same qualitative behavior and only differ in the timing, according to their typical flowering time. The specific findings differ somewhat by region, but an easily explainable pattern or spatial clustering of stations with significant coincidences could not be found.

The findings of this study underline the risk of potential phenological mismatches due to temperature extremes, at least from the plant-ecological perspective. In future studies, it will be especially important to further investigate possible delayed influences of extremely warm temperatures on flowering dates of the following growing season.

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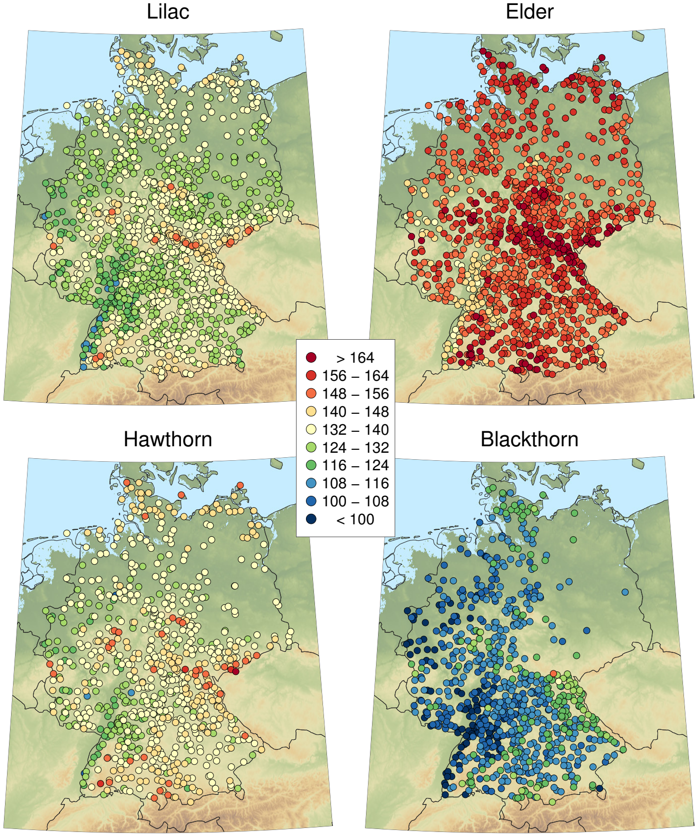

Figure 1. Mean flowering dates (Julian days) of the four analyzed shrub species. The figure only shows those records that contain at least 40 observations.

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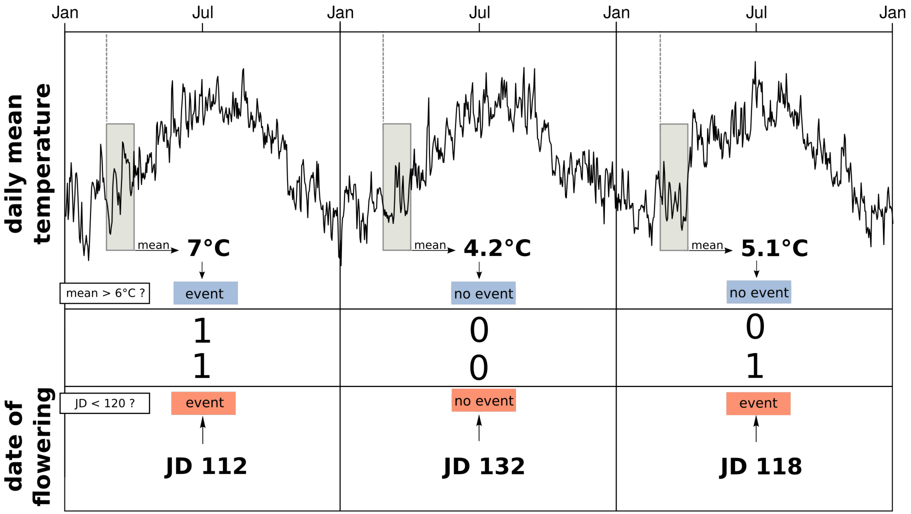

Figure 2. Schematic illustration of the event coincidence analysis used in this work. Upper and lower panels depict the approaches used for defining events based on climatological (daily mean temperature or precipitation) and phenological information (Julian Day of flowering), respectively. For the climate data, windows covering the same time interval during each year are fixed for computing window-mean values. The width and location of these windows are varied throughout the analysis as described in the text. Extreme conditions are defined by the exceedance of certain quantiles of the respective variable of interest (flowering time or window-mean value of the considered meteorological variable for the specified window width and position, i.e., one value per year).

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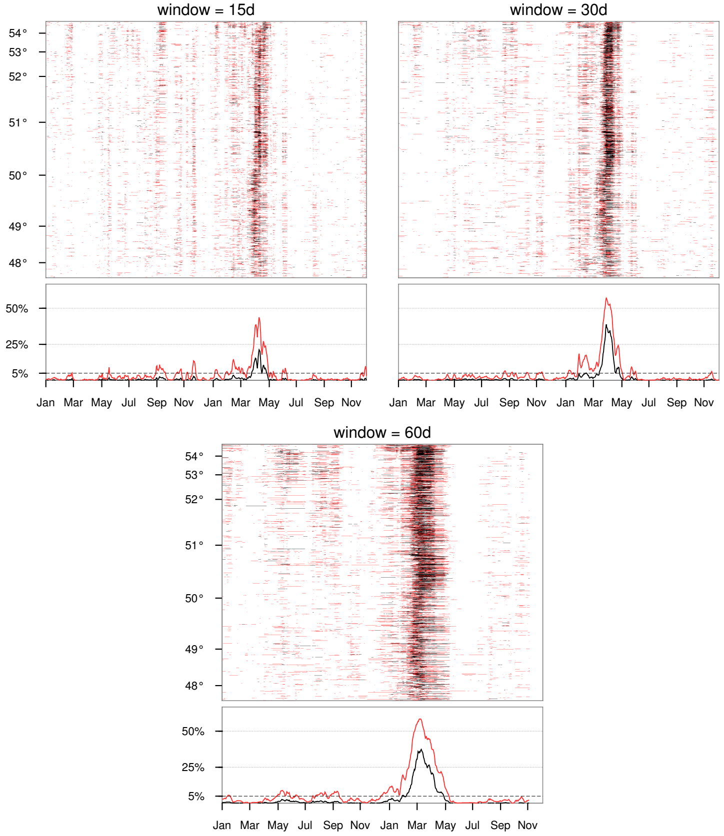

Figure 3. Latitudinal distribution (top panels) and total fraction (bottom panels) of stations with significant coincidences (red: $\alpha = 0.05$, black: $\alpha = 0.01$) between very early Lilac flowering and extremely high window-mean temperatures for three different window sizes. The x axes refer to the starting date of a window. The dashed horizontal lines at 5 % in the lower panels highlight the employed group-significance criterion.

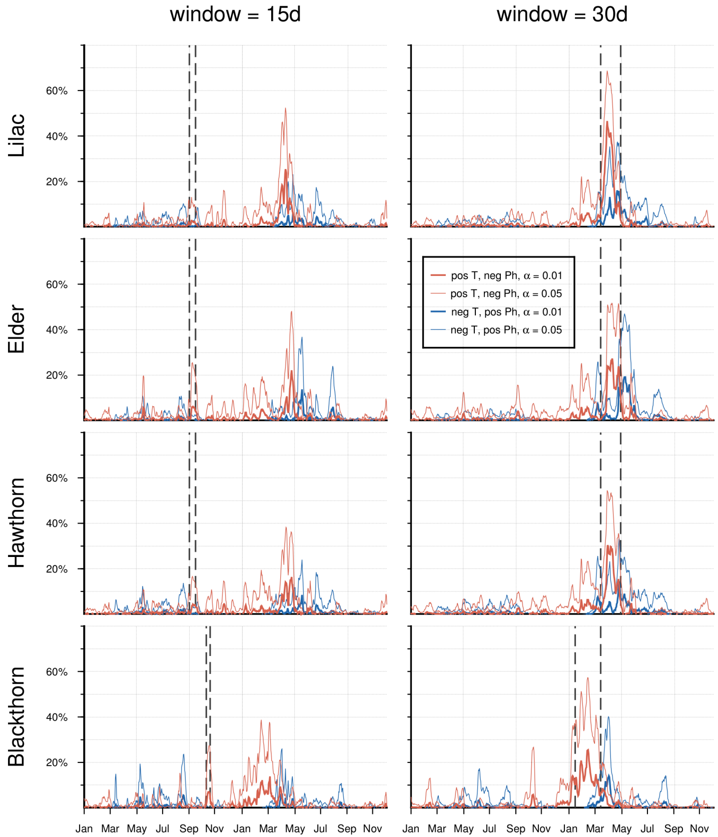

Figure 4. Fraction of stations with significant coincidences between extreme flowering dates and extreme window-mean temperature for the four shrub species and two different window sizes. The *x* axes refer to the starting date of a window, the *y* axes denote the percentage of stations that show significant coincidences for the specific window. Red (blue) lines refer to coincidences of extreme warm (cold) temperatures with extreme early (late) flowering. The vertical dashed lines mark those windows that have been further studied in Figs. 5 and 6.

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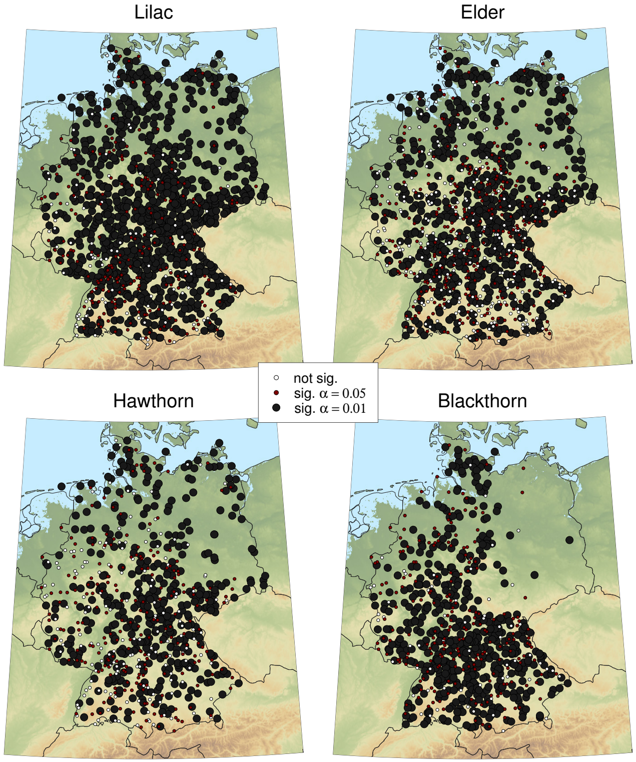

Figure 5. Stations with statistically significant coincidence rates between very early flowering and very warm 30 days window-mean temperatures in the time span from 15 March to 30 April (Lilac, Elder and Hawthorn) and 15 January to 15 March (Blackthorn), respectively. The corresponding intervals are highlighted by vertical dashed lines in the right panels of Fig. 4. Filled black (red) circles mark those stations that show significant coincidence at $\alpha = 0.01$ ($\alpha = 0.05$) confidence level for at least one window during the aforementioned interval. White circles mark stations that have no significant coincidence for any of the windows.

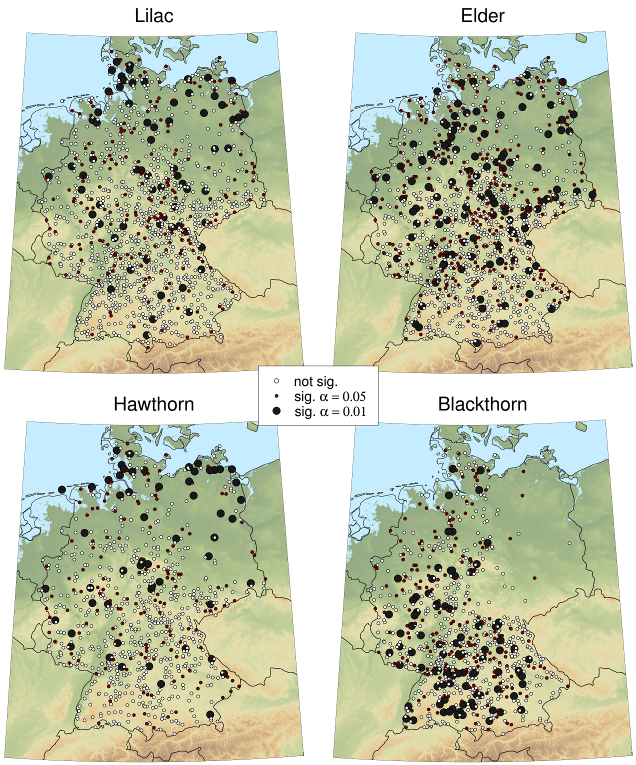

Figure 6. Stations with statistically significant coincidence rates between very early flowering and very warm 15 days window-mean temperatures in the period from 1 to 15 September (Lilac, Elder and Hawthorn) and 10 to 20 October (Blackthorn) of the previous year, respectively. The corresponding intervals are highlighted by vertical dashed lines in the left panels of Fig. 4. Filled black (red) signatures mark those stations, that show significant coincidence at $\alpha = 0.01$ ($\alpha = 0.05$) confidence level for at least one window during the aforementioned interval. White circles indicate stations that have no significant coincidence for any of the windows.

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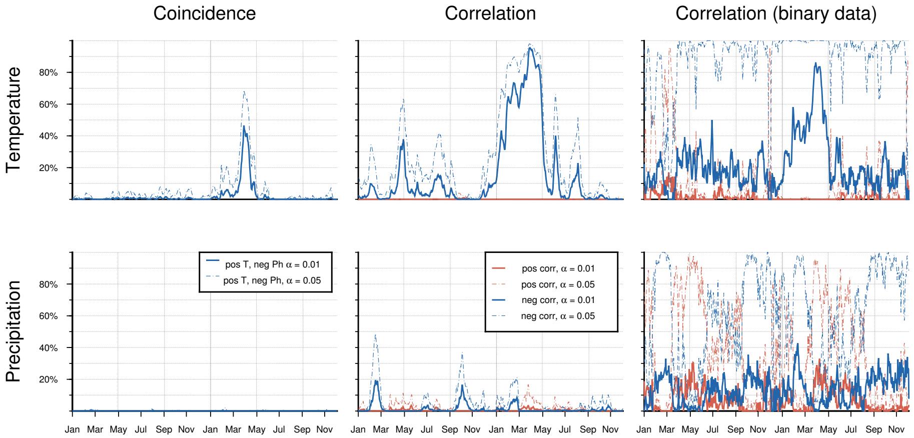

Figure 7. Fraction of stations with significant coincidences (left panels, signifiance test as described in the text), significant correlations between original data (center panels, Pearson correlation with significance according to a standard *t* test), and significant correlations between binary data (right panels, Pearson correlation with significance according to a standard *t* test). The binarization of the time series for the right panels was performed in the same way as for the event coincidence analysis (left panels), see Sect. 3. The figure gives the corresponding results for Lilac flowering with a window size of 30 days.

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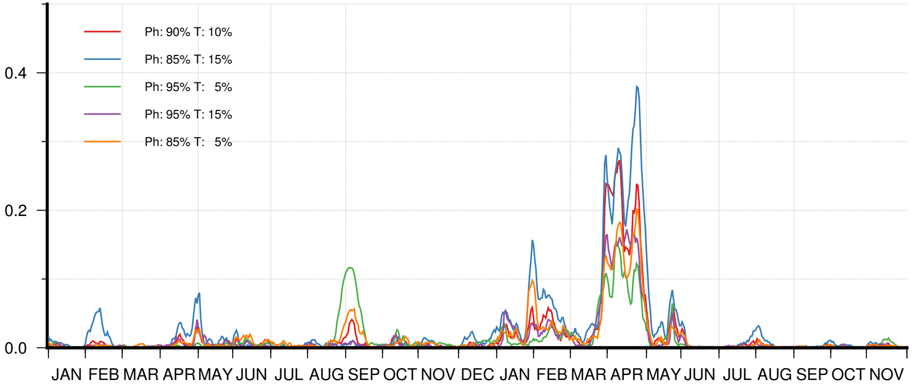

Figure 8. Fraction of stations with significant coincidences ($\alpha = 0.05$) among all phenological stations for 30 days windows and five different threshold combinations of extremely warm window-mean temperature and extremely early Elder flowering. Note that the red line is the same as the bold red line displayed in Fig. 4, second row, center panel.