Consequences of climate change on airborne pollen in Bavaria, Central Europe

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Abstract

Climate change affects the reproductive life cycles of plants, including pollen production, which has consequences for allergic respiratory diseases. We examined climatic trends at eight locations in Bavaria, Southern Germany, with pollen times-series of at least 10 years (up to 30 years in Munich). Climate change in Bavaria was characterized by a rise in temperature, but not during winter. There is also a trend towards a more continental climate in Bavaria, which is significant in the Alps in the south of the territory. The influence of climate change depended on pollen type. Wind-pollinated arboreal species (e.g. *Alnus*, *Betula* and Cupressaceae/Taxaceae) showed advances in the start and end dates of pollen seasons and an increase in pollen load. These changes correlated negatively with late-winter (February) and spring temperatures (April). For herbaceous species, like Poaceae and Urticaceae, an earlier season was observed. Although precipitation is not a limiting factor in Southern Germany, water availability in spring did influence the magnitude of grass pollen seasons. The effect of climatic change on the characteristics of pollen seasons was also more pronounced at higher altitudes, significant at > 800 m above sea level. Our results show that trends for start, end dates and intensity were similar at all locations, but only statistically significant at some. If we assume that earlier and more intense pollen seasons result in increases in prevalence and severity of allergic diseases, then the effect of climate change on public health in Bavaria may be significant.

Keywords

Climate change; Pollen; Precipitation; Temperature; Allergy; Health

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Introduction

Global warming, and mitigating the complex environmental impacts associated with a changing climate, is one of the greatest challenges for humanity (Knutti et al. 2016). Global temperatures have increased by about 0.85 ºC worldwide since the late 19th century (IPCC 2014) and in Central Europe most warming occurred during the 20th century (Anders et al. 2014). Many indicators show that the effects of climate change may increase dramatically if objectives for mitigation are not met (Fawcett et al. 2015), and the most pessimistic scenarios estimate an increase of about 5 ºC by the end of the 21st century in some parts of the world (Guiot and Cramer 2016).

Changes in precipitation are less certain, with both increases and decreases in amount projected depending on geographical area (Anders et al. 2014; IPCC 2014). Although, it is very likely that extreme precipitation events will be more intense and more frequent leading to an increased risk of floods and drought (Sheffield et al. 2012; IPCC 2014).

Climate change has multiple biological effects, ranging from individual physiological processes to ecological relationships between organisms at the community level (Garcia et al. 2014; Morellato et al. 2016; Ummenhofer and Meehl 2017). Climate-induced changes to the reproductive processes of plants may be investigated by examining different traits like the timing of flowering and rates of pollen production. These traits are sensitive to climatic variations and phenological parameters are widely used as bioindicators of climate change, especially in temperate climates (Schröder et al. 2014; Hamaoui-Laguel et al. 2015). Airborne pollen data are representative of large areas (Oteros et al. 2013; Rojo and Pérez-Badia 2014) and aerobiological studies have been used to quantify ongoing changes due to climate change at the regional scale (Makra et al. 2011; Smith et al. 2014; Lind et al. 2016).

Temperature is one of the most important factors driving changes in flowering phenology (Ziska et al. 2019) and advances in reproductive stages have been related to global warming (Walther et al. 2002; Doi et al. 2017; Piao et al. 2019). Besides temperature, plant production is also strongly related to water availability (Bykova et al. 2019). Anthropogenic global warming is the result of increases in atmospheric concentrations of greenhouse gasses such as carbon dioxide, methane, and nitrous oxide, with carbon dioxide being the most important driver of global warming (IPCC 2014). As well as being an important greenhouse gas, carbon dioxide is also an airborne plant fertilizer that stimulates plant productivity (Ziska et al. 2009). In some cases it is difficult to discriminate between the effects of rising temperature and the fertilising effect of carbon dioxide (Katelaris and Beggs 2018). Changes in climate can influence modes of inter-annual variability such as the North Atlantic Oscillation (NAO) in Europe (IPCC 2014), which in turn influences changes in plant phenology (Menzel et al. 2005; Smith et al. 2009; Galán et al. 2016).

Changes in climate are also relevant for public health since alterations in the distribution and flowering phenology of plants may provoke changes in pollen exposure with subsequent impacts on human health (Sheffield et al. 2011; Damialis et al. 2019). Indeed, changes in exposure such as longer pollination periods and higher magnitude pollen seasons may result in more allergic sensitizations, i.e. more allergic patients, and more intense allergy symptoms (Durham et al. 2014; Buters et al. 2015a; Lake et al. 2017; Barnes 2018). A substantial part of the German population is sensitized against pollen (Haftenberger et al. 2013). As a result, climate driven changes to pollen exposure may cause an increase in prevalence and severity of allergic diseases (Shea et al. 2008).

The impacts of climate change vary regionally (Luedeling et al. 2011; Kosanic et al. 2019). The aim of this study is to examine climate-driven changes in plant phenology for the most abundant wind-pollinated plant species in Bavaria, Southern Germany. In order to achieve this, trends in the timing and intensity of airborne pollen concentrations in Bavaria have been examined in relation to temporal and spatial variations in climatic variables over the last three decades.

Material and Methods

Study area

The effects of climate change on airborne pollen in Bavaria, Southern Germany (Central Europe), was examined at eight stations with pollen time-series of at least 10 years in length (Buters et al. 2018; Oteros et al. 2019b): Bamberg (DEBAMB), Bayreuth (DEBAYR), Biedersteiner street of the city of Munich (DEBIED), Erlangen (DEERLA), Thalkirchner street of the city of Munich (DEMUNC), Münnerstadt (DEMUST), Oberjoch (DEOBER) and Zusmarshausen (DEZUSM). The DEMUNC station had a continuous time series of 30 years since 1988. A map of the locations of the stations is given in Figure S1. Also, Figure S2 shows the distribution and abundance of the main studied taxa in the region of Bavaria.

Most of the region of Bavaria is characterized by a Warm Temperate climate (Cfb according to the Köppen-Geiger climate classification) (Kottek et al. 2006; Beck et al. 2018). This type of climate has mean temperatures in the warmest month > 10ºC, and the temperatures of the coldest month ranges between -3ºC and 18ºC. It is also characterized by warm summers without a dry season (Köppen 1936). Within this region, a warmer-dryer climate is represented in the Franconian wine area in the North-West of Bavaria (Würzburg – 177 m a.s.l. with a mean annual temperature of 9.6ºC and mean precipitation of 601 mm) (Oteros et al. 2019a). Also within this region, at the Southern boundary of Bavaria (the Northern Alps), the climate is characterised as Boreal (Dfb, Dfc) with mean temperatures in the coldest month falling below -3ºC and a considerable increase in precipitation (e.g. some of the most extreme conditions are recorded in Zugspitze – mean annual temperature of -4.3ºC and mean precipitation of 2071 mm) (Falk and Mellert 2011; Rubel et al. 2017; Oteros et al. 2019a).

Climate trends

Spatial trends in climatic variables were studied for the period 1989-2018 using the slopes of linear regressions for gridded maps of daily maximum temperature (Tmax), minimum temperature (Tmin), and precipitation (Prec). Note that positive slopes mean an increase in the climatic variable, and negative slopes a decrease. Weekly averages were calculated and, based on these results, seasonal averages of the climatic variables were considered for the analysis. i.e.: Winter – December, January and February; Spring – March, April and May; Summer – June, July and August; Autumn – September, October and November. The number of days with more than 0.5 mm of precipitation was also analysed. Daily gridded meteorological observations were obtained from the E-OBS dataset from the EU-FP6 project UERRA (http://www.uerra.eu), the Copernicus Climate Change Service, and the data providers in the ECA&D project (https://www.ecad.eu) (Cornes et al. 2018). Slopes measuring temperature changes in both lowlands (< 800 m) and highlands (> 800 m above sea level) were analysed and compared with the weather sensitivity of the pollen parameters following the altitudinal gradient, i.e. the relationship between the number of significant correlations with temperatures and the altitude of stations. In addition, trends in the annual thermal oscillation registered in Bavaria were analysed. Thermal oscillation was calculated annually as the difference between the monthly average temperatures of the warmest and the coldest month of the year according to the Continentality Index proposed by Rivas-Martínez et al. (2011).

Trends in temperature and precipitation anomalies were analysed using the gridded meteorological observations (Cornes et al. 2018) for each location of the eight stations with long pollen time-series (i.e. differences between the values of temperature and precipitation for each year with respect to the average of the entire 1989-2018 period). Changes were presented using the slopes of linear regressions for monthly averages. In this case, only one monthly average per season (February in Winter, April in Spring, June in Summer, November in Autumn) was considered. These were the months in each season that showed more intensive changes during the last three decades, as documented in Figure S3. Nonetheless, trend analysis for all months is given in the Figure S4 of the Supporting Information.

Airborne pollen trends

All pollen stations were equipped with volumetric pollen traps of the Hirst design (Hirst 1952), and the process of obtaining and analysing pollen data followed the minimum requirements described by the European Aerobiology Society (Galán et al. 2014). Pollen data collected for the ePIN study (DEBIED, and the pollen data from re-opened stations in 2015) were subject to an external independent quality control process (Smith et al.

2019; Oteros et al. 2019b). Quality control for the long time-series for the other seven stations was performed by the German Pollen Information Service Foundation. For each station and pollen type, daily (24 h period) pollen concentrations were expressed as pollen grains/m^3 of air (Galán et al. 2017). The pollen time-series were checked following the 'quality_control' function of the 'AeRobiology' R package (Rojo et al. 2019). This quality control process excludes incomplete years with too many missing values, so pollen parameters are calculated in a reliable way. Missing data may occur because of temporary technical or other problems in the pollen samplers. Several criteria were used to determine the reliability of the data, such as the possibility to calculate the main pollen season. Details on the inclusion criteria are given in Rojo et al. (2019).

This study focuses on different characteristics of the pollen seasons of the most abundant wind-pollinated plant species in Bavarian pollen spectrum (Rojo et al. 2020). Pollen season start and end dates were defined using the 95% method, which is recommended when a large number of different pollen types are compared from an ecological point of view (Pérez-Badia et al. 2010; Rojo et al. 2016). Whereby the start of the season is defined as the day of the year when 2.5% of pollen is collected, and the end date occurs when 97.5% of the pollen has been reached (Andersen 1991). Pollen amount was characterized using the Annual Seasonal Integral as the sum of the daily pollen concentration (pollen * day/m^3) during the pollen season (Galán et al. 2017). The number of days of high allergenic risk were also calculated and analysed. To establish the clinical threshold, and taking into account that we analysed diverse pollen types, we followed the criteria described by Pfaar et al. (2017) to define high pollen days: 100 pollen/m^3 for arboreal taxa (*Alnus*, *Betula*, Cupressaceae/Taxaceae, *Fraxinus*, *Pinus* and *Quercus*) and 50 pollen/m^3 for herbaceous taxa (Poaceae and Urticaceae). All aerobiological calculations were carried out using the 'AeRobiology' R package (Rojo et al. 2019), which is specifically designed to address these tasks in R Software (R Core Team 2019).

Trends of the pollen parameters were calculated for phenological phases (start and end dates in Days Of the Year - DOY), days exceeding high allergenic thresholds and Annual Pollen Integral. However, not all pollen stations covered the entire study period (see Supporting Information to consult the availability of pollen data). We therefore specified in the results the decades considered for each sampling point. The relationships between pollen parameters and climatic variables were also calculated, i.e. which climatic parameter, in which time period, controls the pollen season in Bavaria. Only the statistically significant trends ($p < 0.05$) are shown.

Results

This study shows that yearly temperatures have increased in Bavaria, Southern Germany during the last three decades. However, the intensity and direction (positive or negative) of these changes were not the same throughout the year (Figure 1) (seasonal variability of climatic changes throughout the year, considering the slopes of the trends of weekly averages, are shown in Figure S3 in the Supporting Information). Temperatures increased in most months. However, late December to late March temperatures decreased slightly but slopes were not significant. April temperatures warmed the most (Figures 1 and 2). Maximum temperature was the meteorological variable with the most significant changes (Figure 1).

Maximum temperatures during the summer and autumn seasons were the climatic factors that displayed the greatest spatial changes across Bavaria (Figure 2). Maximum temperatures showed similar changes throughout the entire Bavaria region, unlike minimum temperatures that showed unclear, spatially heterogeneous, patterns. Precipitation and the number of rainy days during winter clearly increased in the Alps in the south, but trends were not significant in the rest of the territory (Figures 1 and 2). In the same way, the seasonal thermal oscillation in Southern Germany, defined as Continentality Index, changed positively during the last three decades, but this trend was only significant in the foothills of the Alps in the southern part of Bavaria (Figure 3).

More warming trends were observed at higher altitudes, and higher locations revealed more weather sensitive pollen seasons. Here we show that this effect is not only confined to very high altitudes, but also to lower locations in the Alps (Figure 4A). This shows that Bavaria has a shift towards a more continental climate, and this shift is more pronounced at higher altitudes. This altitudinal effect was reflected by changes in airborne pollen, as greater numbers of significant correlations were found between temperature and pollen parameters at higher altitude pollen stations (Figure 4B)

Changes in atmospheric pollen of the most abundant pollen types were examined at 8 pollen stations of Bavaria (Figure 5). Pollen seasons generally tended to start earlier, and the most noticeable advances for the onset of the pollination period were for *Alnus*, Poaceae and Cupressaceae/Taxaceae (Figure 5). The effect on end-dates of the pollination period varied depending on pollen type. The pollen season ended earlier for some tree pollen types such as *Fraxinus*, Cupressaceae/Taxaceae and *Betula*. On the other hand, later end dates or no trends were found for herbaceous pollen types (i.e. Poaceae and Urticaceae).

Trends in pollen amount are frequently contradictory and are very pollen type-dependent. However, we document a clear increase in pollen emission for some tree species like *Alnus*, *Betula* and *Fraxinus*. Cupressaceae/Taxaceae pollen was the pollen type with most significant positive changes in Munich (Figure 5). Also, the number of days of high allergenic risk showed the same direction of change as pollen load, with notable positive trends in *Betula* and negative trends in Poaceae. Trends in the timing and intensity of the birch (*Betula*) and grass (Poaceae) were recorded in Munich (Figure S5, Supporting Information), which is the pollen monitoring station with the longest time series. The amount of birch pollen in Munich increased, although this increase was not statistically significant. The same behaviour, in this case significant, showed the number of days of high allergenic risk. In the case of grass pollen, the Annual Seasonal Integral decreased significantly as with allergenic risk days, but the flowering period extended as a consequence of earlier start-dates of the pollen season (Figure S5, Supporting Information).

Climatic factors influencing characteristics of airborne pollen seasons in Bavaria were investigated, with only significant relationships shown in Figure 6. We observed a clear advance in pollen seasons associated with late-winter and spring warming which is stronger for the main tree pollen types (Figure 7). Later flowering species such as Poaceae were also influenced by spring temperatures, with earlier flowering as a consequence of higher temperatures (Figure 7). In addition, the intensity of grass pollen seasons was governed by the precipitation in spring (Figure 7).

Discussion

Temperatures have increased in Bavaria, Southern Germany, in most months during the last three decades. Maximum temperature was the meteorological variable with the most significant changes, in agreement with previous studies (Gordo and Sanz 2010; Kosanic et al. 2019), and spring temperatures warmed the most. However, winter temperatures decreased slightly although slopes were not significant. Trends towards cooler winter temperatures have also been reported over large parts of the Northern Hemisphere, such as Eastern North America and Northern Eurasia (Cohen et al. 2012). However, this seasonal asymmetry was diluted when longer time periods were analysed. Therefore, winter temperatures continue to follow a positive trend when a longer period of time was considered (Luterbacher 2004). Kosanic et al. (2019) measured climatic trends in Germany and reported a warming of winter temperatures since 1950 but no significant trends have been identified since 1900.

Pollen seasons in Southern Germany generally tended to start earlier as result of rising temperatures, in agreement with other authors (Cleland et al. 2007). The most noticeable advances for the pollen season were for tree pollen types such as *Alnus*, *Betula*, Cupressaceae/Taxaceae and *Quercus*. Also, Poaceae pollen season began earlier although later end dates or no trends were found for herbaceous pollen types (i.e. Poaceae and Urticaceae). These results indicate a general increase in the duration of pollen seasons, which increases the potential pollen risk period for allergic sufferers (Ziska et al. 2019).

Temperature is the main meteorological factor influencing the timing of reproductive cycles in woody plants in temperate latitudes (Campoy et al. 2011). Some of the strongest relationships in South Germany were seen in start-dates of the pollination period of *Alnus* and Cupressaceae/Taxaceae, both winter-flowering species (Werchan et al. 2018; Rojo et al. 2020). One of the most important physiological processes in woody temperate trees is dormancy that favours the cold tolerance to unfavourable seasons (Campoy et al. 2011). After fulfilling chilling thermal requirements, plants require a gradual rise in temperatures, in the so-called forcing period, to break dormancy (Rojo and Pérez-Badia 2014). Chilling temperatures do not seem to be a limiting factor in Bavaria although continued trends towards rising autumn temperatures (November) in the future may endanger the fulfilment of these thermal requirements, i.e. not enough chilling (Luedeling et al. 2011; Rodríguez et al. 2019). We documented a clear relationship of the forcing period in Bavaria for the main tree pollen as end-of-winter (February) and early spring (April) temperatures controlled pollen season characteristics.

The seasonal thermal oscillation in Southern Germany changed positively during the last three decades. More warming trends were observed at higher altitudes, and higher locations revealed more weather sensitive pollen seasons, i.e. a greater climate sensitivity was demonstrated by plants at higher altitudes as greater numbers of relationships were observed between climate variables and the characteristics of the pollen season. Matiu et al. (2016) also documented an increase of seasonal temperature variability towards higher altitude zones of the Alps. Thermal continentality plays a key role in the phytogeographic patterns of vegetation (Vilček et al. 2016) and changes in thermal oscillation and other bioclimatic indices in South Germany can cause changes in pollen phenological parameters related to long-term modifications in plant distribution (Caccianiga et al. 2008; Rubel et al. 2017).

Precipitation is another important key factor for climate change (Miranda et al. 2011). Precipitation increased significantly only in the Alps in the south of the territory and no significant trends were recorded in the rest of the area. Water availability does not seem to be a limiting factor for biological activity in Southern Germany, compared to drier areas like the Mediterranean region (Doblas-Miranda et al. 2017). Nevertheless, temperature is important in regulating water deficit (Vicente-Serrano et al. 2014; Valdes-Abellan et al. 2017). Even in areas where precipitation is not a limiting factor, such as the North of Thuringia in Central Germany, increases in summer temperature increase evaporation and negatively affect plant growth (Zimmermann et al. 2015). The same seems to be happening to Bavaria.

Flowering intensity is a complex process since many variables are involved in different ways. Nevertheless, a general rise in pollen emission from trees relating to climate change has been identified (Ziello et al. 2012; Galán et al. 2016; Lind et al. 2016). For instance, the amount of birch pollen in Munich increased, although this increase was not statistically significant. Also, the number of days of high allergenic risk above the threshold of 100 pollen grains/m^3 increased. On the other hand, most of the significant results for airborne Poaceae pollen in Bavaria indicated decreases in pollen amounts, and number of days of allergenic risk (above a threshold of 30 pollen grains/m^3). The intensity of grass pollen seasons was governed by precipitation in spring, which is in agreement with previous work (Ghitarrini et al. 2017). This weather-based behaviour of grasses could explain the negative trend in the magnitude of grass pollen seasons in Munich. Indeed, a negative, but not significant slope, was observed for spring precipitation in the city. Furthermore, temperature may influence evaporation rates (and thus plant growth) during the spring which has experienced a warming trend in recent years (Bykova et al. 2019). Carbon dioxide levels have also been revealed as an important driver of the productivity in plants (Ziska et al. 2009) and pollen production (Kim et al. 2018). However, analysing the relationship between carbon dioxide and pollen load is not easy in outdoor conditions where associations are masked by other factors.

Biological responses to climate change have consequences on human health when allergenic pollen types are considered. In general, trends towards earlier and longer pollen seasons have been reported (Katelaris and Beggs 2018). We observed a clear advance in pollen seasons associated with late-winter and spring warming. However, we only observed an increase in the length of pollination for herbaceous pollen types such as Poaceae and Urticaceae, which is in agreement with Makra et al. (2011). Airborne pollen levels have been directly related to allergen sensitization profiles in the allergic population (Ariano et al. 2010; Buters et al. 2015a; Lake et al. 2017) and symptoms (Durham et al. 2014).

Trends in the timing and intensity of the birch (*Betula*) and grass (Poaceae) were recorded in the region of Bavaria. In addition to ecological interest, these pollen types have a considerable clinical relevance (García-Mozo 2017; Biedermann et al. 2019) as they are the most important allergenic taxa in Southern Germany (Buters et al. 2012, 2015b). Our findings show that Annual Pollen Integrals of most tree pollen types, e.g. birch pollen, have increased in recent years in Bavaria. Pollen production in herbaceous species, e.g. grasses, have decreased due to future declines in precipitation but flowering periods may extend as a consequence of earlier start-dates of pollen seasons. These trends towards higher (birch) and earlier (grass) pollen seasons, as well as the variations in the number of the days exceeding high allergenic thresholds, have clinical implications for allergic individuals (Katelaris and Beggs 2018).

Conclusions

Climate change influences the characteristics of airborne pollen seasons, and we asked the question whether such changes have been witnessed in Bavaria. We have documented climatic changes in this region and related these to changes in airborne pollen. Although the trends were similar all over the region, they were only statistically significant for some locations or pollen types. Changes were more pronounced at higher altitudes (> 800 m above sea level).

The most notable climatic change in Bavaria during the last three decades was a rise in temperature, especially in spring. Summers and other months were also significantly warmer. There were trends towards colder winters but these were not significant. Increased temperature oscillation indicates a shift towards a more continental climate. Pollen season characteristics are influenced by temperatures during the previous months and our results showed shifting phenological patterns in Bavaria. We documented an earlier flowering and an increase of pollen load and number days of allergenic risk for the most abundant airborne tree pollen types such as *Betula*, Cupressaceae/Taxaceae and *Alnus*. For the herbaceous pollen types Poaceae and Urticaceae, an earlier (but lower Annual Pollen Integral and risk days) pollen season was observed.

Several climatic factors that influence the production, release and dispersal of pollen of allergenic species in Bavaria are the ones that are changing the most (e.g. April temperatures). These climatic factors will continue to be affected by the climate crisis and so we expect the impacts on pollen seasons to become more pronounced. For example, spring temperatures showed the largest changes in Bavaria and correlate strongly with characteristics of airborne pollen seasons of *Alnus*, *Betula* and Cupressaceae/Taxaceae. Moreover, precipitation in Bavaria is a critical meteorological factor for grass pollen production and is changing due to climate change. We therefore feel confident in saying that climate change is already affecting public health in Bavaria, and will continue to be a challenge in the future. Since these impacts are measurable at a regional scale, we believe our research will serve as a base for future studies on effects of climate change on pollen season in other parts of Central Europe and worldwide.

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Declaration of competing financial interests (CFI)

The authors declare they have no actual or potential competing financial interests.

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Legend to the figures

Figure 1. Time series (1989-2018) for selected climatic variables (average maximum and minimum temperature and accumulated rainfall) recorded at pollen stations in Bavaria (central Europe). Only the months with most important changes per season are shown (winter, spring, summer, autumn). Data for all months are shown in Figure S2.

Figure 2. Spatial trends (1989-2018) of selected climatic variables (Tmax: maximum temperature, Tmin: minimum temperature, Prec: accumulated precipitation; Rain days: number of days with more than 0.5 mm rain registered) in Bavaria (Central Europe). The colours represent the slopes of the trends obtained from linear regressions by using three-month averages of the climatic variables. Winter: December, January and February; Spring: March, April and May; Summer: June, July and August; Autumn: September, October and November. Significant trends (p-values < 0.05) are enclosed with black lines.

Figure 3. Trend of the annual thermal oscillation (measure for continentality) registered in Bavaria 1989-2018. Thermal oscillation was calculated annually as the difference between the monthly average temperatures of the warmest and coldest months of the year. The colours represent the slopes of the trends obtained from linear regressions. Significant trends (p-values < 0.05) are enclosed with black lines.

Figure 4. A) Slopes measuring temperature changes in comparison to the altitude for different months; B) Relationship between the number of significant correlations of temperatures and pollen parameters and the altitude for each pollen station. The length of the time series for all stations was reduced to 15 years for the same pollen types in order to enable comparison between pollen stations.

Figure 5. Summary of trends in the timing and intensity of pollen seasons for the most abundant pollen types in Bavaria. Dots represent the slope for a station (maximum 8 stations) for a characteristic of the pollen season. A dark dot indicates $p < 0.05$, the dot shape indicates information about the studied period for each station (see Figures S5-S12 for more information about available data for each pollen station).

Figure 6. Heatmap of the relationships between characteristics of the pollen season and climatic variables from Figure 1. Intensity of the colour represent the number of significant stations (only changes with $p < 0.05$ are shown) for a specific relationship, a red colour indicates a positive relationship (positive slopes) and a blue colour indicate negative relationship (negative slopes).

Figure 7. Specific relationships between characteristics in the timing and intensity of pollen seasons and seasonal climatic variables. The most relevant relationships of the Figure 5 are detailed, and only significant stations are shown. Station abbreviations are given in the text.

Supporting Information

Figure S1. Location of aerobiological sampling points in the Bavaria region, Southern Germany.

Figure S2. Distribution and abundance of the main studied taxa in the region of Bavaria. Abundance probability maps (1x1 km) of the arboreal species from the genera *Alnus*, *Betula*, *Fraxinus*, *Quercus* and *Pinus* were provided by the European Atlas of Forest Tree Species (De Rigo et al., 2016). Presence/Absence map (100x100 m) of grasslands was provided by the Copernicus Land Monitoring Service (Copernicus Land Monitoring Service 2020).

Figure S3. Slopes of weekly climatic variables (average maximum and minimum temperature and accumulated rainfall) recorded in Bavaria, Central Europe (1989-2018). Only the geographical location of the 8 pollen stations were considered.

Figure S4. Trends in climate anomalies (average maximum and minimum temperature and accumulated rainfall) recorded in Bavaria, Central Europe (1989-2018). Only the geographical location of the 8 pollen stations were considered.

Figure S5. Linear trends (red dashed line) for the main characteristics of the pollen seasons (according to pollen timing and pollen intensity) of birch (A) and grasses (B) for the longest historical pollen time-series in Bavaria (Munich, DEMUNC). Blue line represents the smoothed trend using the LOESS smoother and the confidence interval (95%).

Figure S6. Availability of the data for *Alnus* pollen in the Bavaria region (Central Europe).

Figure S7. Availability of the data for *Betula* pollen in the Bavaria region (Central Europe).

Figure S8. Availability of the data for Cupressaceae/Taxaceae pollen in the Bavaria region (Central Europe).

Figure S9. Availability of the data for *Fraxinus* pollen in the Bavaria region (Central Europe).

Figure S10. Availability of the data for *Pinus* pollen in the Bavaria region (Central Europe).

Figure S11. Availability of the data for Poaceae pollen in the Bavaria region (Central Europe).

Figure S12. Availability of the data for *Quercus* pollen in the Bavaria region (Central Europe).

Figure S13. Availability of the data for Urticaceae pollen in the Bavaria region (Central Europe).