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ORIGINAL ARTICLE

Integration of flowering dates in phenology and pollen counts in aerobiology: analysis of their spatial and temporal coherence in Germany (1992–1999)

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Abstract We studied the possibility of integrating flowering dates in phenology and pollen counts in aerobiology in Germany. Data were analyzed for three pollen types (*Betula*, *Poaceae, Artemisia*) at 51 stations with pollen traps, and corresponding phenological flowering dates for 400 adjacent stations (< 25 km) for the years 1992–1993 and 1997–1999. The spatial and temporal coherence of these data sets was investigated by comparing start and peak of the pollen season with local minima and means of plant flowering. Our study revealed that start of birch pollen season occurred on average 5.7 days earlier than local birch flowering. For mugwort and grass, the pollen season started on average after local flowering was observed; mugwort pollen was found 4.8 days later and grass pollen season started almost on the same day (0.6 days later) as local flowering. Whereas the peak of the birch pollen season coincided with the mean flowering dates (0.4 days later), the pollen peaks of the other two species took place much later. On average, the peak of mugwort pollen occurred 15.4 days later than mean local flowering, the peak of grass pollen catches followed 22.6 days after local flowering. The study revealed a great temporal divergence between pollen and flowering dates with an irregular spatial pattern across Germany. Not all pollen catches could be explained by local vegetation flowering. Possible reasons include long-distance transport, pollen contributions of other than phenologically observed species and methodological constraints. The results suggest that further research is needed before using flowering dates in phenology to extrapolate pollen counts.

Keywords Flowering · Long-range transport · Phenology · Pollen · Spatial variability

Introduction

The impact of climate change on aeroallergens and related allergic diseases, although of enormous importance, has been somewhat neglected (Beggs 2004). Allergies have become more and more frequent in the Western world, especially pollen related allergies. Many studies report that prevalence to pollen related allergic diseases has risen in recent decades (e.g. Haahtela et al. 1990; Aberg et al. 1996; Beggs and Bambrick 2005). Major aeroallergens in Europe comprise pollen of the genus/family *Alnus, Corylus, Betula, Poaceae, Artemisia and Ambrosia*. Especially, birch pollen is very common in temperate and northern regions and can cause severe allergic reactions. Almost 20% of the German population is sensitised to birch pollen (Nowak et al. 1996).

The impacts of climate change on aeroallergens include changes in the amount of pollen, the pollen allergenicity, the pollen season, and the plant and pollen distribution (Beggs 2004). In particular, there is strong evidence from various studies that observed higher temperatures due to

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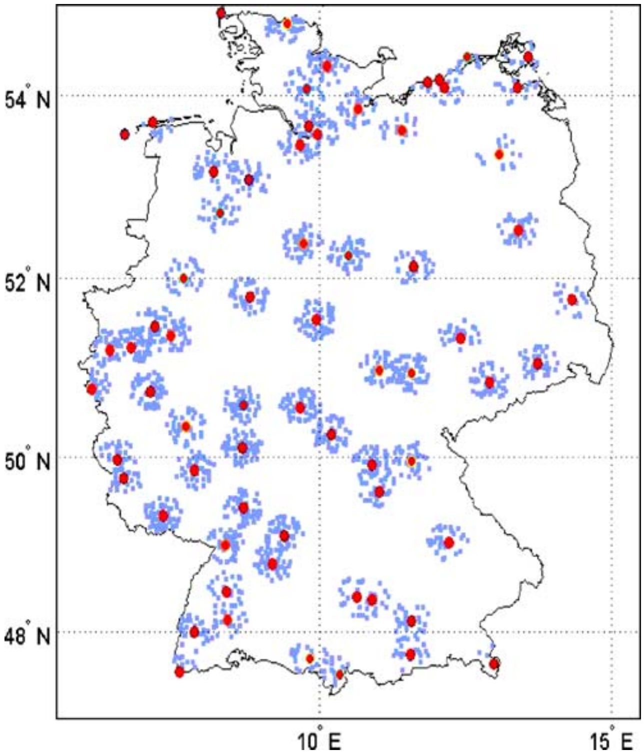


Fig. 1 Distribution of pollen traps (*large dots*) and corresponding phenological stations (*small dots*) at ≤ 25 km distance in Germany

climate change are associated with an earlier start of plant flowering in spring and summer (e.g. reviews by Menzel and Estrella 2001; Walther et al. 2002; Parmesan and Yohe 2003; Root et al. 2003; Traidl-Hoffmann et al. 2003) and an earlier onset of the pollen season in the northern hemisphere (Frei 1998; Emberlin et al. 2002; Rasmussen 2002; Beggs 2004). However, not only have trends to an earlier, but also longer and more intense, pollen season for various species been reported (e.g. Spieksma et al. 1995, 2003; Jager et al. 1996; Emberlin et al. 2002), but also a higher allergenicity of pollen (Beggs and Bambrick 2005; Beggs 2004).

Compared to the relatively short history of pollen measurement in pollen traps, phenological observations of starting dates of flowering provide a higher station density and longer records, sometimes covering the entire last century. Thus, a spatial and temporal integration of both phenological and pollen records would constitute a convenient enlargement of the pollen data base, especially for climate impact and epidemiological studies.

Allergic disorders constitute an important public health problem of ethic and economic dimensions, as airway diseases, i.e. hay fever and asthma, reduce well-being and ability to work, finally leading to higher expenses in the health sector. Thus, methods to forecast pollen flight periods and their intensities are necessary to help the sufferers, affected people, and physicians to optimise medication and behaviour. Several systems of pollen forecasts have been installed in different European countries, e.g. in Germany by the German Meteorological Service (DWD) and the Polleninformationsdienst (PID). These institutions forecast the start of the pollen season as well as the day to day variation of its intensity for different pollen types (http://www.pollenstiftung.de/index.php?inhalt=pollenvorhersage; Huynen et al. 2003). Chuine and Belmonte (2004) published a first pollen prediction model based only on daily mean temperatures. However, the obligatory parameterisation was only available for regions in Spain and France. In contrast, most methods used to forecast pollen flight are based on semi-empiric methods, i.e. integration of flowering observations, weather forecast and information on pollen counts in pollen traps. The system installed by the German Meteorological Service, for example, incorporates daily observations of the start of the flowering period at around 400 stations in Germany. Thus, for the application and improvement of pollen forecasts, an integration of flowering and pollen records is also most beneficial.

Airborne pollen, with its aerodynamic diameter of c. 10 µm, contributes to the organic, solid components in the coarse particulate matter (PM10). Pollen is, due to its size, very mobile. Therefore, all efforts to forecast the pollen season via daily temperature data and/or phenological (flowering) observations may emerge as obsolete if most of the pollen found in traps does not originate from the studied surroundings. If the spatial dispersal of pollen on a larger scale is of importance, the models would need to account for this and incorporate variables such as large-scale weather patterns. There are first indications that long-range transport of pollen might be significant. Kasprzyk (2003) reported for a station in Poland that sometimes flowering of the local trees cannot be the source of the pollen found in the traps. Pollen of exotic taxa that originated at least 1,000 km away was detected in Canada (Cambon et al. 1992) and in Greenland (Rousseau et al. 2003). Faced with these possibilities of long-range transport, there is a need to clarify to what spatial and temporal extent local pollen production (defined by phenology) is not the source for pollen found in the neighbouring traps.

The overall goal of this paper is to analyse the spatial and temporal coherence between locally observed flowering dates and pollen counts in pollen traps. Although the causal relationship (flowering = production of pollen) seems to be clear, there exists an enormous lack of knowledge in this field. As a study area we chose Germany because it provides an extremely dense network of phenological observers and sufficient number of pollen records by traps. The primary goal of the integration of flowering and pollen data further offers the possibilities: (1) to enlarge and reconstruct spatially and temporally the

Table 1 Number of pollen observation stations with different pollen records in Germany

Year	*Betula*	*Poaceae*	*Artemisia*
1992	39	43	40
1993	44	45	38
1997	48	51	44
1998	46	49	35
1999	47	48	38

pollen records for climate change impact and epidemiological studies, (2) to improve and optimise the model framework for pollen forecasting, especially as phenological observations are cheaper and might allow earlier warnings, and (3) to quantify the occurrences of local/long-range transport.

Materials and methods

Pollen data

The German pollen monitoring network, run by the Polleninformationsdienst (PID, www.pollenstiftung.de) comprises 51 stations with pollen traps (Burkard type) across Germany (see Fig. 1), predominantely at lower altitudes hower few also at 600– 800 m a.s.l. The traps are positioned at 10–12 m above ground in order to measure regional pollen distribution, and to reduce the influence of plants in direct neighbourhood.

At each station, daily averages of pollen numbers per cubic metre ambient air are counted and, as a minimum, the pollen for six groups (*Corylus, Alnus, Betula, Artemisia, Poaceae* and *Secale*) are identified. For our analyses, we had pollen data for birch (*Betula*), grass (*Poaceae*) and mugwort (*Artemisia*) for the years 1992–1993 and 1997–1999 available. For each pollen type, the annual start day of pollen flight (start), and the day of the maximum pollen count (peak) was determined. The start of the pollen season was defined as the date when 1% of the total number of pollen grains of the year has been reached, provided that one of the following 6 days shows another pollen count (Krämer et al. 2001). Table 1 summarises the number of pollen stations for each year and pollen type.

Phenological data

Phenological data were provided by the German Meteorological Service (DWD). In the DWD phenological network volunteers at around 1,600 stations observe defined plant development stages. The following three phases were selected for our study: beginning of flowering of birch (*Betula pendula* L.), of meadow foxtail (*Alopecurus pratensis* L.) and of mugwort (*Artemisia vulgaris* L.). Flowering of orchardgrass (*Dactylis glomerata* L.) was not included in the analysis as its onset dates were much later than the start of the grass pollen flight period. The guidelines for phenological observers (Deutscher Wetterdienst 1991) specify that observations should be made at normal sites with average microclimatic conditions, and the observation sites should be within 50 m of a fixed elevation range. Beginning of flowering is defined as the day on which the first blossoms are fully open on at least three spots on the observed object. In addition, the observer has to check if wind pollinated plants emit pollen. For our investigation, we selected a subset comprising those stations within 25 km distance around the pollen traps (Fig. 1). Due to the dense phenological network, records of more than 400 phenological stations were available for each species and year.

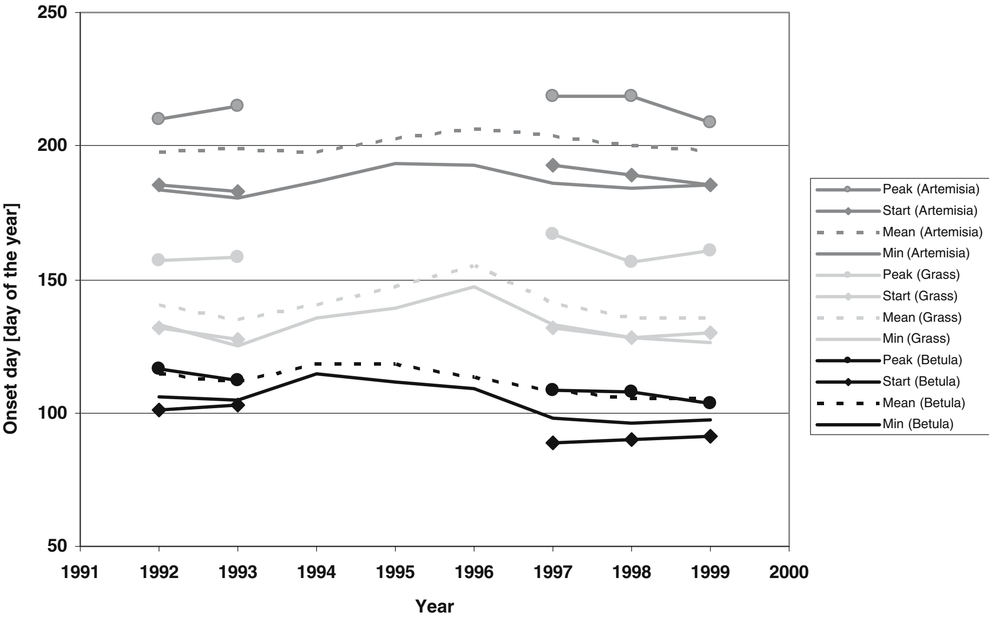
Methods of analysis

All observed dates within the pollen and the phenological data set were converted to Julian date. For each pollen station and species, we determined the first observed phenological flowering date (min) and the mean of all observed flowering dates (mean) at the surrounding phenological stations ($\leq$ 25 km). These two phenological variables were subtracted from the respective dates of the start and peak of the pollen flight period in order to investigate the temporal differences between pollen and phenological measures. A negative deviation signified an earlier occurrence of pollen in the ambient air as detected by the pollen traps than flowering of the respective species observed in the local surrounding. Special emphasis was given to the spatial variability and regional pattern of these time spans. In addition, to analyse the geographic influence, a regression of the difference between pollen season (start/peak) and first flowering (min) and the geographic coordinates, latitude and longitude was calculated.

Results

The average annual dates of the start of the pollen season of birch, mugwort and grass compared to the observed start of flowering dates suggested a close connection between these records (see Fig. 2). However, a closer look revealed that, e.g. for birch, the start of the pollen season at the pollen stations occurred earlier than the average local minima of the start of flowering. For mugwort and grass, this relationship is only true in few years. Whereas the peak of the birch pollen season coincides with the mean flowering dates, the pollen peaks of the other two species took place much later. Thus, for birch pollen, all comparisons of flowering dates (min, mean) with measures of the pollen season (start, peak) are presented, but for mugwort

Fig. 2 Annual mean onset dates of the start (start) and peak (peak) of the pollen season at the pollen stations in Germany and of the earliest and mean flowering dates of the respective phenological stations (see Fig. 1)



and grass the graphs are restricted to comparisons with min flowering dates.

In Table 2, the remarkable results for the birch pollen season are further examined for the different years. At 56% (1998) to 79% (1997) of the pollen stations, the start of the pollen season was observed earlier than the first flowering in the surroundings. The time span between these events was up to 57 days. However, in fewer cases, the start of pollen season was much later than the first flowering (up to 34 days). In very rare cases, even the peak of the pollen season was noted before the first flowering dates. On the other hand, it could take several weeks until the peak followed the first observed phenological flowering, e.g. in the year 1992 at Münnerstadt, the pollen peak was 63 days after the onset of flowering. In all other years, the pollen peak followed the phenological observation by about 1 month (e.g. 38 days in 1998).

The skewness of the difference between the start of pollen flight and flowering is not consistent; the years 1992, 1998 and 1999 have a negative skewness, 1997 is flat and 1993 has a positive skewness. The difference between the peak of pollen season and flowering the skewness in all years is >0. In all years, the deviation is higher for the difference of the start of pollen season and flowering than for the difference the peak of pollen season and flowering. 1992 has the highest value (16.69 days for start, 15.64 days for peak), and the smallest standard deviation is in 1993 (7.87 days for start, 7.07 days for peak).

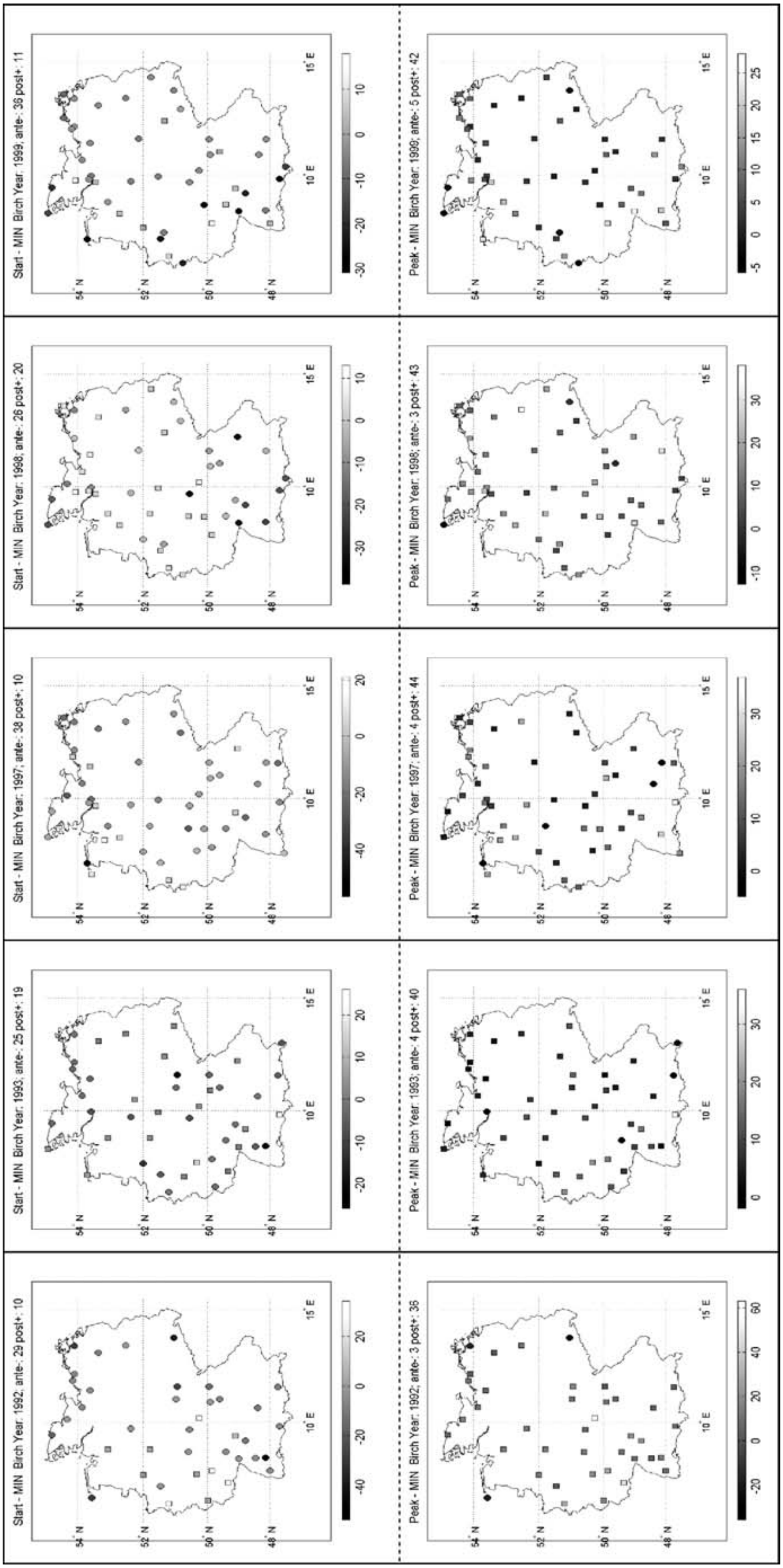
The spatial analyses of the time spans between the pollen count (start, peak) and the respective flowering dates (min, for birch also mean) around the pollen stations are presented in Figs. 3, 4, 5 and 6.

For birch (Fig. 3), the time span between first pollen observations and the phenological onset of flowering varied

Table 2 Differences between start and peak of the birch (*Betula*) pollen season and the respective earliest starting dates of flowering (min), *n* (neg) number of stations where flowering is observed later than the pollen measures, *n* (pos) number of stations where flowering is observed earlier than the pollen measures

Year	*n* (neg)	*n* (pos)	Min	Max	Mean	Median	SD
Start - min							
1992	29	10	−54	34	−4.95	−4.0	16.69
1993	25	19	−26	26	−1.57	−2.0	7.87
1997	38	10	−57	21	−9.5	−9.5	12.26
1998	26	20	−39	13	−5.91	−1.5	11.68
1999	36	11	−31	18	−6.21	−4.0	10.93
Peak - min							
1992	3	36	−36	63	10.38	9.0	15.65
1993	4	40	−2	36	7.7	7.0	7.07
1997	4	44	−5	37	9.96	8.5	9.28
1998	3	43	−13	38	11.54	10.0	9.28
1999	5	42	−6	28	6.51	5.0	7.66

Fig. 3 Difference in days between start of the birch (*Betula*) pollen season (*upper row*), peak of the pollen season (*lower row*) and earliest flowering (min) at pollen stations in Germany (1992–1993, 1997–1999). *Circle*, negative value: start, peak of pollen season before start of flowering. *Square* positive value: start of flowering before start, peak of the pollen season



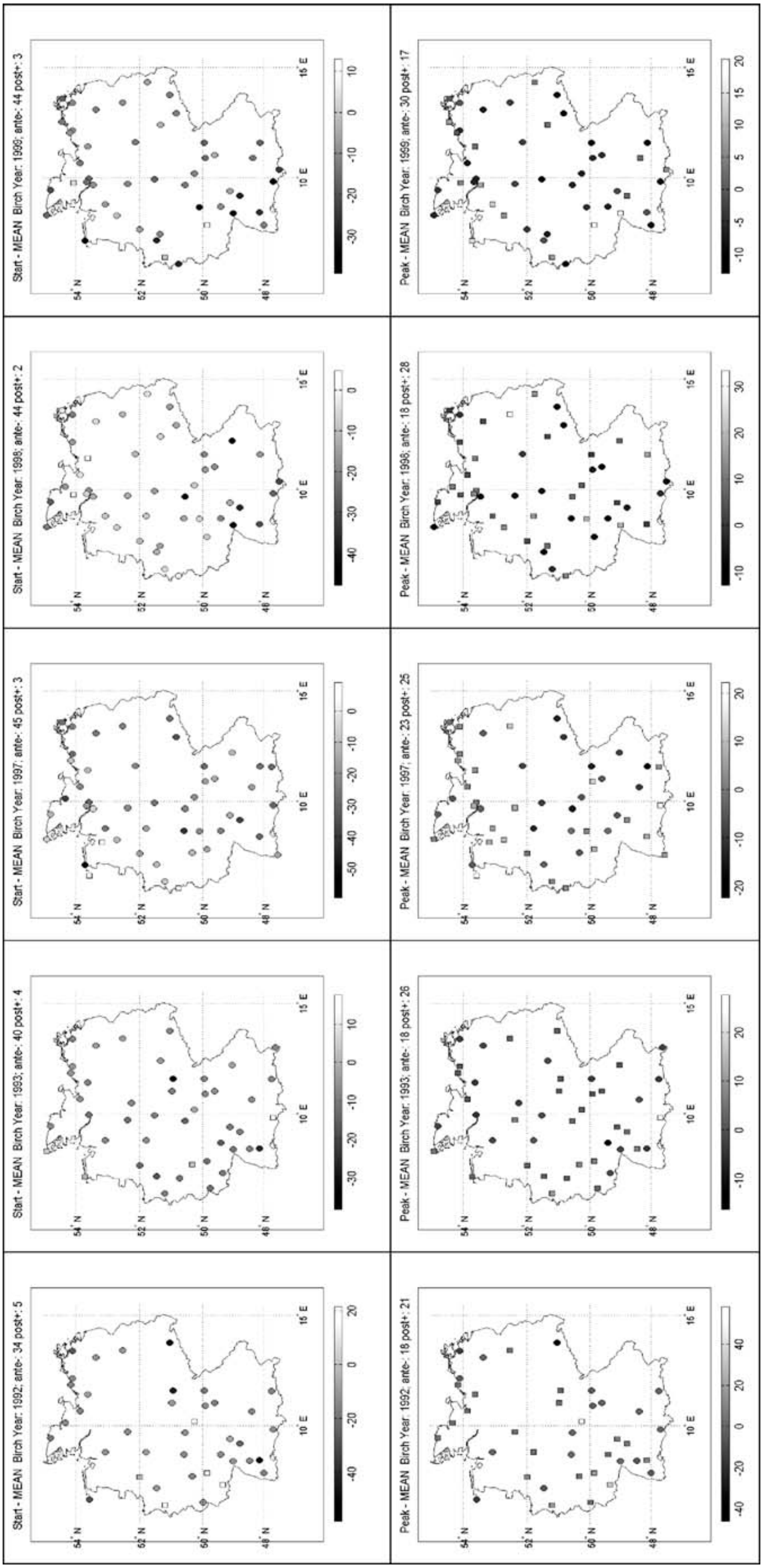


Fig. 4 Difference in days between start of the birch pollen season (*upper row*) peak of the pollen season (*lower row*) and mean flowering dates (mean) at pollen stations in Germany (1992–1993, 1997–1999). *Circle,* negative value: start, peak of pollen season before mean flowering. *Square* positive value: mean flowering before start, peak of the pollen season

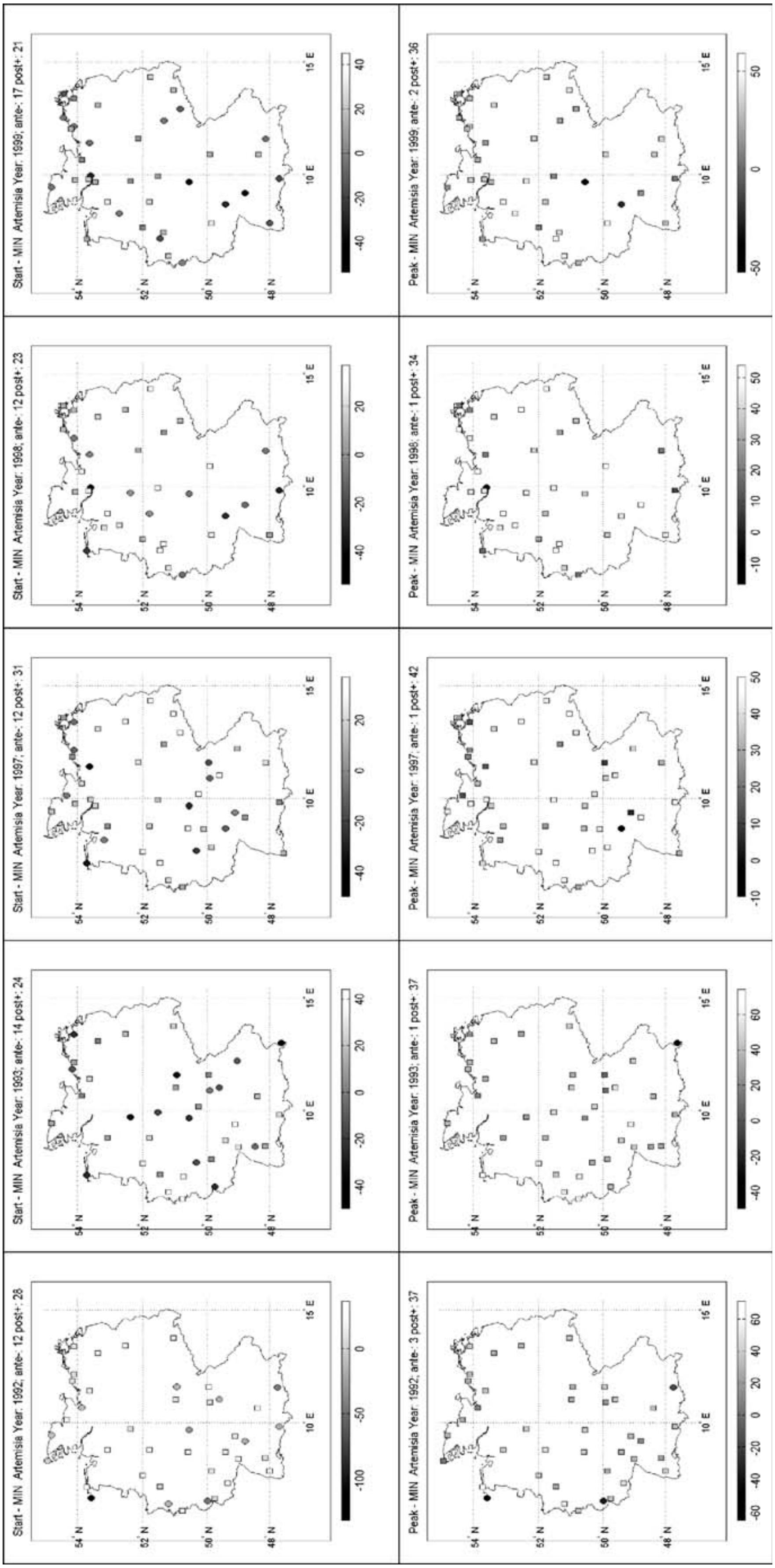
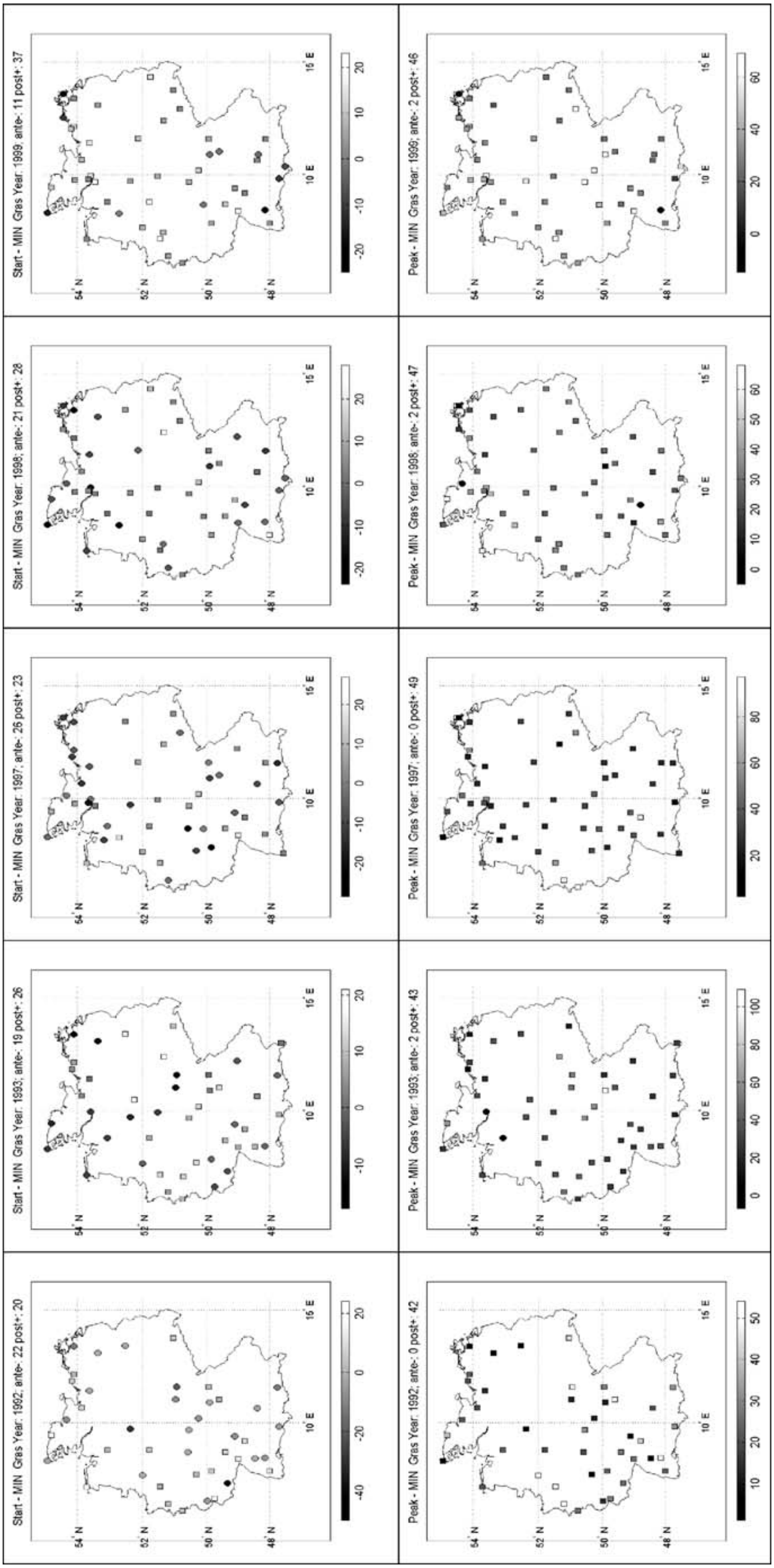


Fig. 5 Difference in days between start of the mugwort (*Artemisia*) pollen season (*upper row*), peak of the pollen season (*lower row*) and earliest flowering (min) at pollen stations in Germany (1992–1993, 1997–1999). *Circle* negative value: start, peak of pollen season before start of flowering. *Square* positive value: start of flowering before start, peak of the pollen season

Fig. 6 Difference in days between start of the grass (*Poaceae*) pollen season (*upper row*) peak of the pollen season (*lower row*) and earliest flowering (min) at pollen stations in Germany (1992–1993, 1997–1999). *Circle* negative value: start, peak of pollen season before start of flowering. *Square* positive value: start of flowering before start, peak of the pollen season



strongly. Sites where the start or the peak of the pollen season was observed before the local flowering dates have negative values as equivalent for differences in days. Only at sites with positive values was the phenological observation noted before the pollen was caught in the trap, thus phenological monitoring would support regional pollen forecast. It is obvious that when comparing start of the pollen season and first flowering, more stations exhibited negative values (= not explained by local flowering) than when comparing pollen peak and first flowering.

There was no regional pattern apparent. For a statistical justification, a regression of the differences between start/peak of pollen season and flowering against latitude and longitude of the pollen station as well as mean altitude of the respective surrounding pheno stations (≤ 25 km) was calculated. For both cases, the results showed that there is no geographic dependence (start: $P > F$ 0.2 and $R^2 = 0.067$; peak: $P > F$ 0.001 and $R^2 = 0.07$).

Stations with strong negative values are located close to the northern coast in 1997 and 1999, e.g. in 1997 the start of the pollen season in Norderney was 57 days before birch flowering occurred on local plants. But in 1992 and 1993, the stations with the largest negative values were situated in the south and east, while in 1998 the greatest difference emerged in central and southern Germany.

The day of the peak pollen observation compared to the first flowering at neighbouring stations for birch displayed a more uniform pattern. For the years 1993, 1997 and 1999, the difference between observed local flowering and peak of pollen was negative only at a few stations. Larger deviations were found in 1992 at Dresden, where the pollen peak was noted 36 days before the first locally observed flowering of birch, and in 1998 at Westerland, where there was a difference of 13 days between the peak of pollen and the first locally observed flowering.

When comparing the measures of the birch pollen season (start, peak) to the mean (mean) of the flowering dates for each pollen station (Fig. 4), these differences shift, as anticipated, to higher negative values, especially for the start of the pollen season. Only at very few stations was the start of the pollen season measured after the phenological event was noted. In 1997 and 1999, even for the peak of the pollen season, more stations had negative values than positive ones. In the other years, the distribution was almost even. Within the 5 years analysed, we identified occurrences with a reported peak of pollen season more than 30 days later than mean flowering: in 1992 in Münnerstadt, the peak of pollen season occurred 58 days after mean flowering; in 1998 a time gap of 33 days appeared in Berlin-West; and one of 31 days in Homburg.

The spatial distribution of the time spans between the start and the peak of the pollen season for mugwort and the first observed flowering displayed a very heterogeneous pattern (Fig. 5). Some stations showed a great discrepancy between pollen counts and flowering, e.g. in 1992 the first pollen was measured 132 days before first flowering at Borkum, while in all other years early pollen observations were made around 50 days before flowering occurred. But at most stations, pollen findings were later than the observed flowering. Here, the difference reached up to 45 days in 1999. The peak of mugwort pollen found in the traps was, with the exception of a very few stations, later than the observed flowering. These stations exhibiting earlier pollen than flowering were not consistent over the years, including seaside, alpine, and Rhine rift stations. The majority of the stations had dates of peak of the pollen flight around 10–50 days after onset of flowering.

For the grass pollen flight period (Fig. 6), the time span between start of the pollen season and flowering of *Alopecurus pratensis* at neighbouring stations varied. In 1992, the maximum time span occurred at Homburg where pollen was found 50 days before flowering started. In all following years (1993, 1997–1999), there were smaller differences between pollen and flowering dates. The largest positive deviation was found at Freiburg in 1998, where the grass pollen season started 28 days later than the observed flowering. For the clear majority of the stations, the start of the pollen season was a week before or after flowering was observed. In nearly all cases (stations and years), the peak of the pollen season was detected later than onset of flowering, with the exception of two stations at a time in 1993, 1998 and 1999, which were not identical.

Discussion

Our results clearly demonstrate that *Betula* exhibited the greatest temporal divergences between pollen caught in pollen traps and observed onset of flowering in Germany. These time spans were by far too large to assume pollen dispersal exclusively from local plants. The phenological observations used in this analysis stem from various stations located within 25 km around the traps, and thus their data should represent the regional vegetation's behaviour. From publications by Rapiejko (1995), we know that first pollen grains at ground level might be up to 2 weeks earlier than at roof level. Thus, it can be assumed that the temporal mismatch observed in our study would even be larger if the pollen traps were situated at ground level. Of course, for some offsets between pollen findings and local flowering there may be simpler explanations such as mistakes within the pollen data, or the flowering data. For example, if the exact onset date of flowering is not identified correctly, pollen might have been emitted before the noted date. Another reason could be associated with the definition of the start and peak of the pollen season, due to the fact that both are dependent on total pollen load of the year (Krämer et al. 2001). In addition. the weather conditions at the site might influence the distribution of pollen, because no or reduced pollen flight will occur when it is rainy or calm, but this hardly explains the compelling differences between local flowering and pollen findings over all observed years, especially not pollen catches before local flowering.

Therefore, due to size of *Betula* pollen (c. 10 μm aerodynamic diameter), the most likely explanation for the long time span between observed local flowering and observed pollen is long-range transport. Different studies have confirmed that the regular maximum distance of anemophilous pollen transport is around 500 km (Van de Water et al. 2003; Rousseau et al. 2003). But some weather conditions can lead to far longer transport, e.g. in Greenland, different pollen types had been found travelling at least 1,000 km (e.g. Cambon et al. 1992; Rousseau et al. 2003) and in the arctic, pollen was identified originating from approximately 3,000 km away (Campbell et al. 1999). This fact might be the reason for our findings that the start of the pollen season was not well explained by local phenology. Even the peak of the pollen concentration was mainly found before local vegetation started flowering. The peak concentration depended more on local plants' flowering; only at few stations did we observe that local plants' average flowering was before the start of the pollen season.

Grass pollen appeared not as mobile; fewer stations exhibited first pollen observations before flowering. The peak strongly depended on local flowering of grass. The differences between start of pollen and of flowering season of *Artemisia* was very irregular; some events could stem from long-distance transport. Especially in 1992, we identified several such events. Further research is planned to investigate where the pollen found in Borkum, an island in the North sea, originated from (e.g. by backwards trajectories). The prevailing wind direction there is west, so pollen could have originated from far away.

In general, observations of flowering in phenological networks might help to explain pollen catch in traps, but our analysis points out that phenological observations with the current methodology are not nearly sufficient. First, pollen transport over various distances might lead to pollen findings before or after local vegetation starts flowering (Kasprzyk 2003). Other possibilities to explain this temporal mismatch comprise a noteworthy contribution of other than the phenologically observed species to the pollen loads in the traps (e.g. other species of the genus *Betula*, such as *Betula pubescens*, and of the family Poaceae, such as *Dactylis glomerata*) and difficulties in identifying the first flowering specimens in a larger surrounding. Thus, information on flowering is of tremendous importance, not only for single specimens at average microclimatic sites, but also at population or ecosystem levels.

Pollen catches and phenological data displayed a wide range between their events (start, peak, min, mean), thus further research is needed before using flowering dates in phenology to extrapolate pollen counts. The fact that the pollen peak of *Betula* occurred before local flowering started raises further unanswered questions concerning the distribution of pollen in central Europe. Further research is required into long-distance transport as well as regional dispersal of pollen, because it is still unknown how strongly these events influence pollen concentrations. First attempts have been made with trajectories (e.g. Smith et al. 2005; Jarosz et al. 2004; Rousseau et al. 2004; Bourgeois et al. 2001; Cabezudo et al. 1997; Cambon et al. 1992). Smith et al. (2005) tried to locate the regional origin within the UK, whereas Jarosz et al. (2004) calculated forward trajectories from the source to find the area of deposition. The studies by Rousseau et al. (2003, 2004), Bourgeois et al. (2001) and Cambon et al. (1992) discussed the origins of pollen from almost vegetation-free regions in the far north. There might be a high potential to support and develop new pollen forecast practices by modelling air mass / pollen transport via trajectories, finally reducing the impact of pollen induced allergies on suffering individuals and optimising their medication.

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