



Influence of climate change on flowering season of birch in the Czech Republic

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Abstract

This paper analyzes a long-term (1991–2019) flowering period of birch in the Czech Republic. Temporal and spatial evaluation in timing of beginning and end of flowering (F_{begin} and F_{end}) and flowering period (F_{period}) of *Betula pendula* were investigated in different zones of the Czech Republic. The field observations were carried out at 44 sites of the Czech Hydrometeorological Institute phenological network; the detailed analysis including growing degree days (GDD) evaluation to F_{begin} and F_{end} onsets and time of flowering were made at 9 sites in different altitudes. The trends and Pearson's correlation coefficients between F_{begin} (F_{end}) and GDDs were calculated as well. The timing of both phenological stages showed a significant advance to earlier onsets (e.g., – 7.0 d per decade at Měděnec station) and the time of flowering shortens (e.g., – 3.8 d per decade at Rokytnice station). Nevertheless, the most marked shift was observed for mountain area in the north-western and north-eastern part of the Czech Republic. In contrast, the smallest shift was found in the southern part of the Czech Republic. The shift of the GDD values fluctuates from negative to positive values. Pearson's correlation coefficients calculated for both phenophases and period of flowering of *Betula pendula* showed the highest values in F_{period} (e.g., 0.846 at Modrava station) and in F_{end} (e.g., 0.711 at Rokytnice station) as well. Thus, our results indicate due to global warming symptoms that birch pollen allergy may appear earlier in the year but for a shorter period.

Keywords Phenology · Spring · Flowering · Air temperature · Growing degree day

Introduction

Phytophenology, the timing of recurrent plant development, such as sprouting, flowering, and leaf coloring, is determined by the abiotic conditions. Plant phenological observations are widely used as bioindicators of climate change; phenology has become an important tool in the

climate change research. Phenological data play also an important role in other disciplines such as agriculture, ecology, wildfire management, forestry, tourism, and medicine. Pollen allergy has a remarkable clinical impact all over Europe, and the allergenic content of the atmosphere varies according to climate, geography, and vegetation (D'Amato et al. 2007).

Numerous studies from around the world have shown significant changes in the onset of phenological phases during the twentieth century (e.g., Menzel 2000; Poikolainen et al. 2016). For example, according to Menzel (2000), it was found that in Europe, based on International Phenological Gardens' data (1959–1996), spring events such as leaf unfolding have advanced on an average of 6.3 days (– 0.21 day per year), while autumn events such as leaf coloring have been delayed by 4.5 days (0.15 day per year).

The broad-leaved tree *Betula pendula* is the most widespread species of the *Betula* spp. (birch) genus in Europe. To know a shift in timing of birch pollen season is important – *Betula* spp. is well-known as a significant aeroallergen. Understanding the spatiotemporal patterns of changes in pollen season timing and levels is thus important in assessing

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climate impacts on aerobiology and allergy caused by allergic airborne pollen (Zhang et al. 2014) such as birch. Climate change is likely to affect allergic disease (Smith et al. 2014) and impacts on allergens may be one of the most important consequences of climate change for human health (Beggs 2015).

Phenological observations might be useful in determining areas with increasing pollen release and moreover could be used as an input data for atmospheric dispersion models. Although, definitions of phenophases and observational methodologies may vary from one country to another (van Vliet et al. 2003), it is important to analyze the phenological phases closely associated with the period of flowering.

The aim of this paper were as follows:

- (1) to make spatial evaluation of the beginning (F_{begin}) and end of flowering (F_{end}) from CHMI phenological stations in the three main periods (1991–2000; 2001–2010; 2011–2019),
- (2) to calculate the trend in phenological development of birch flowering including the number of days during flowering in periods 1991–2019 in different climatic zones,
- (3) to evaluate the sums of growing degree days above threshold above 5 °C (GDD) to phenophase onset and during period of flowering calculated since January 1,
- (4) to calculate Pearson's correlation coefficients between phenological stage (F_{begin} , F_{end}), time of flowering (F_{period}), and GDD.

Material and methods

Nowadays, the Czech Hydrometeorological Institute (CHMI) operates with a phenological network of wild plants following methodology for voluntary observers (Anonymous 2009; Coufal et al. 2004). There are observed 11 phenological phases in birch; in this paper we focused on phases connected with flowering (pollen release) such as the beginning of flowering (F_{begin}) and end of flowering (F_{end}). The phenological dates are listed in the day of year (DoY), and phenological phases are often also mentioned in BBCH (Bundesanstalt, Bundessortenamt and Chemical Industry) codes. The BBCH-scale is a system for a uniform coding of phenologically similar growth stages of all mono- and dicotyledonous plant species (Meier 1997). According to the BBCH scale, the phenological phase beginning of flowering (F_{begin}) = BBCH 61 and end of flowering (F_{end}) = BBCH 69.

Observations are made from the same tree individuals (3–5) at least twice a week. Description of F_{begin} (we observe only the male flowers) is subsequent: catkins are soft and opened, anthers are fully visible, and pollen is already released. F_{end} is

defined as follows: the catkins are empty, turn dry and dark, and fall on the ground.

Phenological data were obtained from CHMI database PHENODATA and were checked in the following ways:

- (1) outliers were excluded from data series if the difference in the phenophase onset among the closest phenological station was larger than 1 month (Štěpánek et al. 2012),
- (2) data quality was verified by using the 3-sigma method (www.investopedia.com).

For the study of long-time series, the following analytical tools were used: regression analysis, Pearson's correlation coefficients (r), and geographic information system (GIS). Phenological trends were studied using onset dates (in day of year – DoY) of phenological events (phases); the mean temporal change (days per year) was evaluated using the regression slope. Pearson's correlation coefficient (r) was applied to investigate the relationship between phenological time series and mean of growing degree days to phenophase onset and during period of flowering.

Thermal time (cumulative heat) is often expressed in growing degree days (GDD). GDD is calculated by subtracting a base temperature from the daily mean temperature, and the GDD values less than zero are set to zero. The summation over time is related to the development of plants, insects, and disease organisms. According Glickman (2000) base temperature is 5 °C: $GDD = t_{\text{avg}} - t_{\text{base}}$, where t_{base} = cardinal temperature minimum for plants = 5 °C.

We have used accumulated growing degree days (GDD) – sum of GDD from day of year DOY_1 to DOY_2 .

Here, DOY_1 was set as January 1, and DOY_2 was the day of the year that marks the end of the time period for GGD calculation – in our case it was the date of beginning of flowering (F_{begin}) and end of flowering (F_{end}).

The maps were processed (as an input was used in the mean phenophase onset) using geographic information system – Application Clidata-GIS (ArcGIS version 10.4.1), method Clidata-DEM (method of local linear regression between the measured or calculated value and the digital relief model with dependence on altitude (e. g., Tolasz et al. 2007)).

For the calculation of pheno-climatological characteristics were used mean air temperature (so-called “technical series”) from CHMI climatological stations in daily step. For the data processing of “technical series”, the software packages AnClim (Štěpánek 2007), LoadData, and ProClimDB (Štěpánek 2008) were used.

Maps were created from CHMI phenological network (44 sites – elevation range was from 155 m asl (Doksany) to 1102 m asl (Modrava)), the detailed study was performed at 9 phenological stations located in different parts of the Czech Republic (Lednice, Běleč nad Orlicí, Chřibská, Březina, Český Rudolec, Brandov, Rokytice v Orlických horách, Měděnec, and Modrava). The climate conditions of

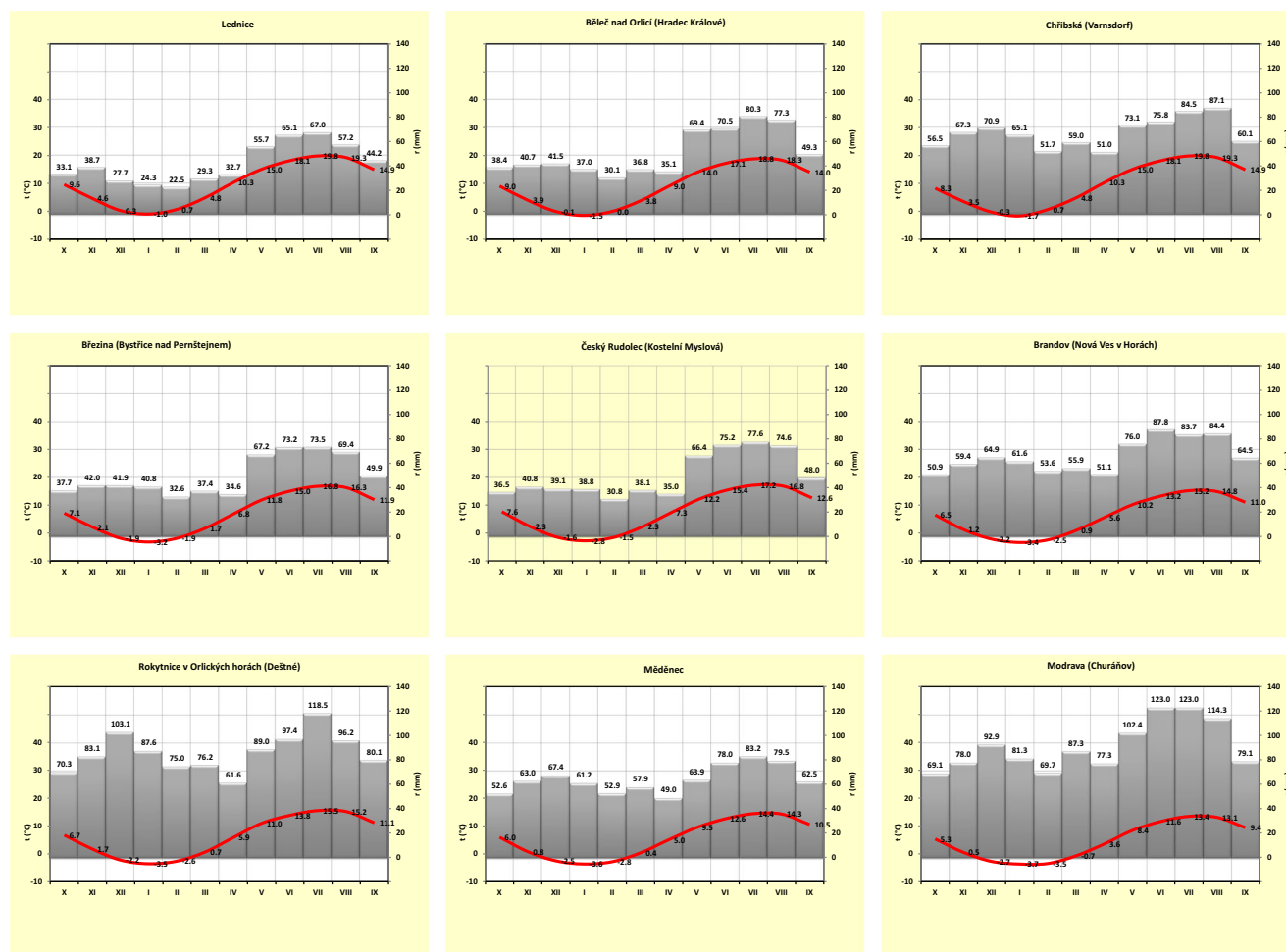


Fig. 1 Climagrams of phenological stations

the individual localities are characterized by modified Walter–Lieth climagram (Kožnarová and Klabzuba 2010) based on the agrometeorological year with long-term average data

1961–2015 (Fig. 1, Table 1). The agrometeorological year starts on October 1 and ends on September 30 (Kožnarová and Klabzuba 2010).

Table 1 Climatological characteristics of phenological stations (link to Fig. 1), stations are listed by altitude

	t_{year} (°C)	$\text{abs } t_{\text{max}}$ (°C)	$t_{\text{max VII}}$ (°C)	$t_{\text{min I}}$ (°C)	$\text{abs } t_{\text{min}}$ (°C)	$t_{\text{min}} > 0.0$ °C (days)	r_{year} (mm)	$\text{abs } r_{\text{max}}$ (mm)	$r > 0.1$ mm (days)
Lednice	9.7	38.1	26.4	−4.3	−27.8	266	497.3	82.4	129
Běleč	8.9	37.9	24.5	−4.3	−24.7	266	606.5	101.5	171
Chřibská	9.4	37.1	23.1	−4.2	−26.1	260	802.8	89.4	204
Březina	6.9	35.8	22.5	−6.0	−26.1	234	600.3	98.0	174
Český Rudolec	7.3	37.1	23.1	−5.4	−24.3	266	600.9	118.1	179
Brandov	5.9	34.1	19.8	−5.7	−24.5	230	793.7	142.7	203
Rokytnice	6.1	33.6	20.6	−5.9	−26.0	223	1038.1	203.6	292
Měděnec	5.4	32.7	20.0	−5.9	−21.4	224	771.9	92.5	218
Modrava	4.6	34.2	18.7	−6.5	−25.5	207	1097.3	135.3	211

Notes

t_{year} = average year air temperature (°C), $\text{abs } t_{\text{max}}$ = absolute maximum of air temperature, $t_{\text{max VII}}$ = average monthly maximum of air temperature of the warmest month, $t_{\text{min I}}$ = average monthly minimum of air temperature of the coldest month, $\text{abs } t_{\text{min}}$ = absolute minimum of air temperature, $t_{\text{min}} > 0.0$ °C = average count of days with air temperature minimum > 0.0 °C, r_{year} = average year precipitation total (mm), $\text{abs } r_{\text{max}}$ = absolute maximum of daily precipitation total, $r \geq 0.1$ mm = average count of days with total precipitation ≥ 0.1 mm

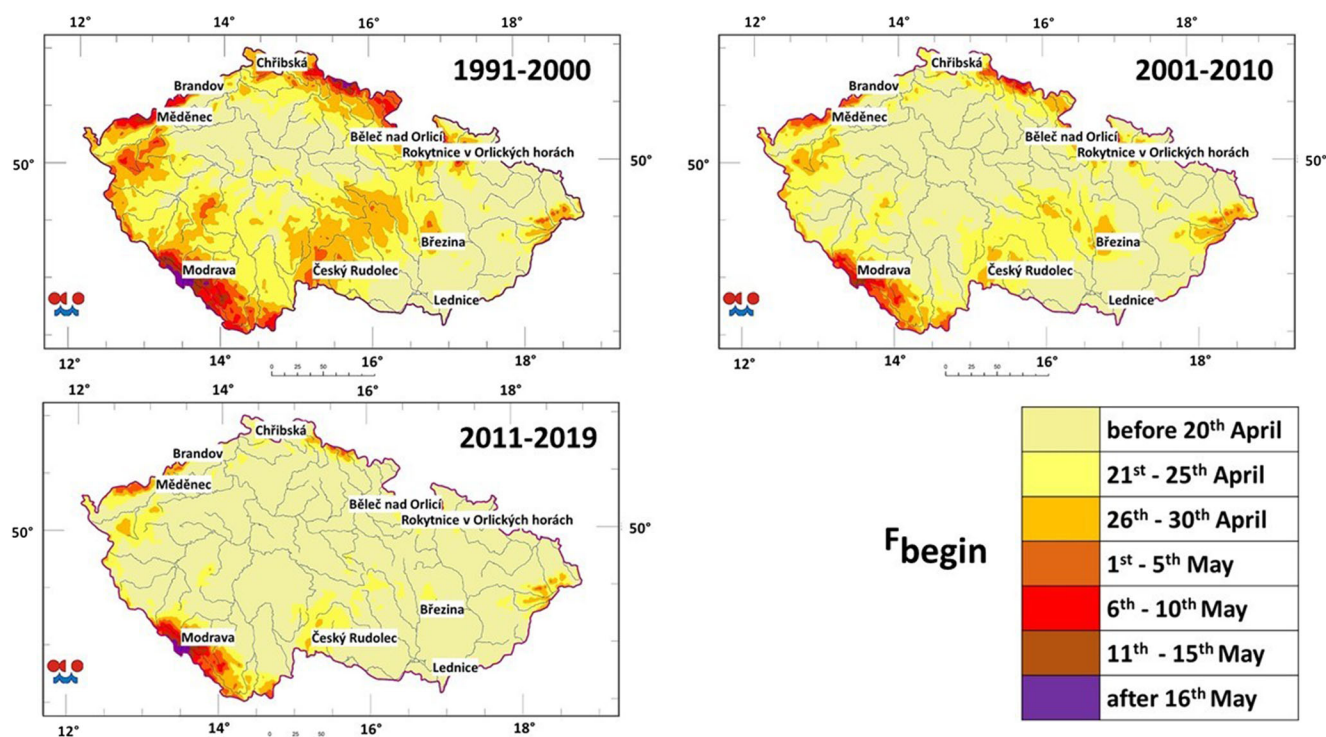


Fig. 2 Beginning of flowering (F_{begin}) of *Betula pendula* in the Czech Republic within period 1991–2000, 2001–2010, and 2011–2019

Results

The time range of F_{begin} is nearly one month in the area of the Czech Republic – mean limit values in maps are April 20 and May 16 (Fig. 2). The mean annual onset of birch beginning of

flowering has changed during the 29 years period 1991–2019. In periods 1991–2000, the beginning of flowering of birch started on 37.6% of the Czech Republic area before April 20, in period 2001–2010 it was 60.5% of the area, and in period 2011–2019 it was even on 81.5% of the area. The

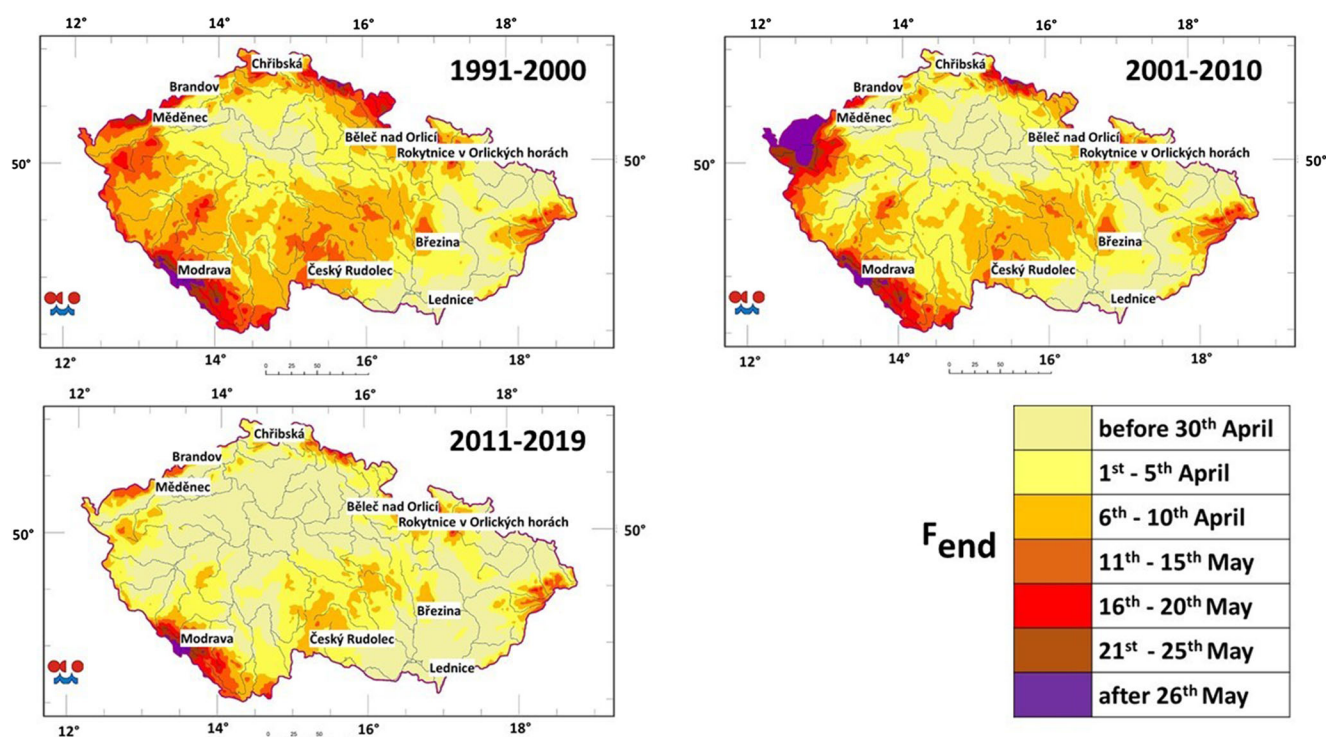


Fig. 3 End of flowering (F_{end}) of *Betula pendula* in the Czech Republic within period 1991–2000, 2001–2010, and 2011–2019

Table 2 Descriptive statistics for F_{begin} , F_{end} , and F_{period} of *Betula pendula* in period 1991–2019 (in day of year), stations are listed by altitude

Station	Average	Median	Upper quartile	Lower quartile	Standard deviation	Minimum	Maximum	Variation range	Variation coefficient
Beginning of flowering (F_{begin})									
Lednice	98	96	95	100	4.8	88	108	20	4.9
Běleč	106	106	101	113	8.3	91	125	34	7.9
Chříbská	113	114	106	118	10.0	93	136	43	8.9
Březina	115	116	109	120	7.5	96	125	29	6.5
Český Rudolec	114	114	110	117	5.1	103	127	24	4.5
Brandov	117	118	110	122	9.3	105	148	43	7.9
Rokytnice	121	120	117	126	8.8	107	141	34	7.3
Měděnec	121	125	114	129	9.4	104	136	32	7.8
Modrava	134	137	126	141	10.0	116	153	37	7.4
End of flowering (F_{end})									
Lednice	116	116	111	120	6.9	102	129	27	6.0
Běleč	123	121	119	126	6.4	107	137	30	5.2
Chříbská	126	125	121	128	10.4	108	149	41	8.2
Březina	128	128	127	131	6.3	113	140	27	4.9
Český Rudolec	126	126	123	130	6.3	110	142	32	5.0
Brandov	131	131	127	135	8.0	118	155	37	6.1
Rokytnice	133	132	126	139	10.2	116	167	51	7.7
Měděnec	133	135	125	140	9.8	114	146	32	7.4
Modrava	149	148	141	152	11.4	132	191	59	7.6
Period of flowering (F_{period})									
Lednice	18.3	18	14	21	5.7	8	30	22	31.4
Běleč	16.5	16	12	19	6.0	8	35	27	36.5
Chříbská	13.4	13	10	15	4.2	7	25	18	31.0
Březina	13.1	12	10	15	4.1	7	22	15	31.4
Český Rudolec	12.4	12	11	15	3.6	5	21	16	28.7
Brandov	13.2	13	11	15	3.3	7	20	13	25.4
Rokytnice	11.4	10	8	14	5.3	5	26	21	46.7
Měděnec	11.3	11	10	12	2.3	8	16	8	20.1
Modrava	14.2	13	10	17	7.2	5	38	33	50.9

similar trend can be also seen by the end of flowering (Fig. 3). The situation was as follows: the end of birch flowering before April 30 (mean limit values for F_{end} are April 30 and May 26) was during the period 1991–2000 on 17.7% of the Czech Republic area, during the period 2001–2010 it was on 26.6% of the Czech Republic area, and in period 2011–2019 it was almost double – on 52.7% of the Czech Republic area. The beginning of flowering later than May 16 was within the first decade on 0.6% of the Czech Republic, in the second decade it was only on 0.03% of the area, and in the third decade it was on 0.3% of the area. The end of flowering later than May 26 was in period 1991–2000 on 0.8% of the area, in period 2001–2010 it was on 1.8% of the area, and in period 2011–2019 it was on 0.4% of the Czech Republic area.

Descriptive statistics for beginning and end of birch flowering including period of flowering presents Table 2. Based on the observed terms of F_{begin} and F_{end} phenophases

of *Betula pendula* from 1991 to 2019, the beginning of flowering was first observed at Lednice station (165 m asl) on March 29, 2014, and the end of flowering on April 12, 2014, at the same station. The latest date of F_{begin} was observed at Modrava station (1102 m asl) on June 2, 2010, and end of flowering at the same station (on July 10, 2010). The mean time of flowering oscillates from 11.3 days (Měděnec station) to 18.3 days (Lednice station). The most common mean period of flowering between 14 and 15 days was on 53.8% of the Czech Republic area (1991–2000), on 44.2% of the Czech Republic area (2001–2010), and on 42.1% of the Czech Republic area (2011–2019). Variation coefficients take on similar values in F_{begin} and F_{end} . F_{begin} is the range of values between 4.5 and 8.9, F_{end} is between 4.9 and 8.2. The range of variation coefficient's values by period of flowering is much larger (from 20.1 to 50.9). The period of flowering is longer in

Table 3 Descriptive statistics for GDD to F_{begin} , F_{end} , and period of flowering (F_{period}) of *Betula pendula* in period 1991–2019 ($^{\circ}\text{C}$), stations are listed by altitude

Station	Average	Median	Upper quartile	Lower quartile	Standard deviation	Minimum	Maximum	Variation range	Variation coefficient
Beginning of flowering (F_{begin})									
Lednice	105.8	98.0	76.9	122.0	42.0	40.6	203.4	162.8	39.7
Běleč	120.7	117.7	101.6	141.3	28.9	63.9	168.7	104.8	23.9
Chřibská	114.8	107.8	86.3	124.8	57.5	15.0	342.1	327.1	40.1
Březina	94.3	84.7	70.9	100.2	40.6	37.0	197.7	160.7	43.1
Český Rudolec	102.5	104.0	83.1	121.1	26.1	47.5	150.1	102.6	25.5
Brandov	84.8	85.2	68.7	98.8	25.8	34.0	146.0	112.0	30.5
Rokytnice	99.4	91.1	68.3	120.4	39.2	49.8	218.5	168.7	39.5
Měděnec	91.7	93.2	75.9	108.1	23.9	38.8	145.0	106.2	26.1
Modrava	109.6	110.0	89.7	124.7	39.8	27.1	241.6	214.5	36.4
End of flowering (F_{end})									
Lednice	219.6	220.8	181.1	249.3	54.0	130.4	366.8	236.4	24.6
Běleč	230.6	237.6	189.8	267.4	47.8	119.8	332.2	212.4	20.7
Chřibská	199.1	175.7	145.0	230.3	75.2	106.6	431.2	324.6	30.8
Březina	170.7	161.2	141.1	198.9	51.4	68.4	287.0	218.6	30.1
Český Rudolec	181.7	190.6	153.8	204.8	36.7	101.8	256.3	154.5	20.2
Brandov	159.4	160.3	139.7	173.0	32.8	93.9	235.5	141.6	20.6
Rokytnice	173.4	156.9	135.9	209.8	61.4	88.5	393.8	305.3	35.4
Měděnec	150.7	142.5	131.7	166.2	37.1	60.7	238.3	177.6	24.7
Modrava	190.3	165.8	147.8	226.8	82.3	63.8	480.6	416.8	43.2
Period of flowering (F_{period})									
Lednice	113.9	114.0	80.5	145.4	42.8	42.1	213.4	171.3	37.6
Běleč	109.9	115.2	76.5	131.3	43.0	26.1	196.2	170.1	39.2
Chřibská	84.2	77.5	58.6	96.5	39.3	21.8	180.8	159.0	36.7
Březina	76.4	66.2	57.4	89.3	33.8	29.7	157.5	127.8	44.2
Český Rudolec	79.3	70.6	56.8	96.9	28.0	40.4	167.5	127.1	35.3
Brandov	74.6	73.2	60.1	88.0	22.4	31.0	129.9	98.9	30.0
Rokytnice	74.1	69.0	44.3	88.6	41.4	6.4	219.1	212.7	55.9
Měděnec	59.0	60.3	40.6	73.9	28.0	0.9	110.1	109.2	47.5
Modrava	80.7	68.3	38.0	112.0	66.8	13.5	341.5	328.0	82.7

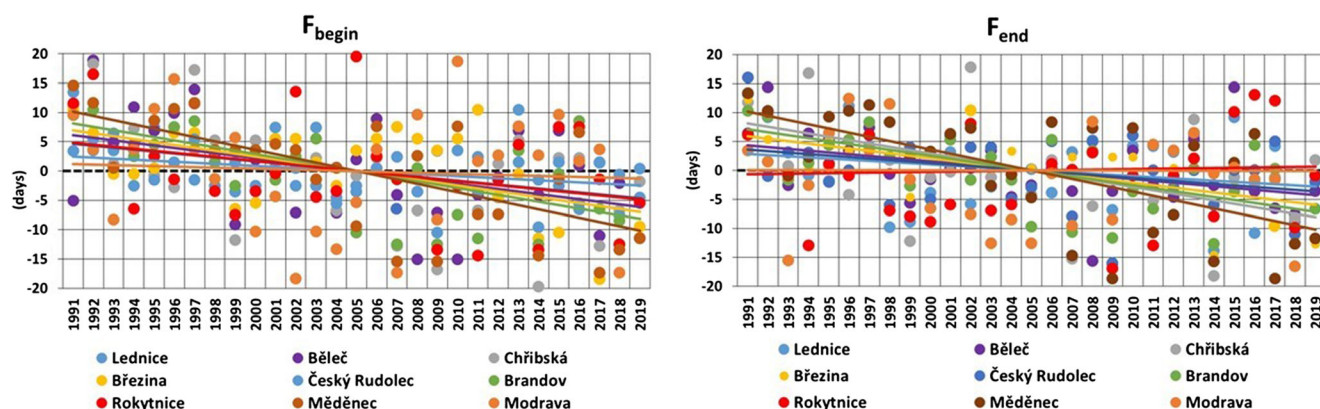
**Fig. 4** Linear trend of deviations of F_{begin} and F_{end} from 1991 to 2019 in the Czech Republic

Table 4 Linear regression equations and coefficients of determination (link to Fig. 4), stations are listed by altitude

	Beginning of flowering (F_{begin})		End of flowering (F_{end})	
	Equation	R^2	Equation	R^2
Lednice	$y = -0.1778x + 100.22$	0.0992	$y = -0.2030x + 3.04$	0.0620
Běleč	$y = -0.4365x + 112.62$	0.1981	$y = -0.3064x + 4.60$	0.1664
Chřibská	$y = -0.5824x + 121.52$	0.2458	$y = -0.5773x + 8.66$	0.2246
Březina	$y = -0.4990x + 121.97$	0.3250	$y = -0.4246x + 6.37$	0.3250
Český Rudolec	$y = -0.3320x + 118.50$	0.3077	$y = -0.2562x + 3.84$	0.1216
Brandov	$y = -0.5803x + 126.19$	0.2800	$y = -0.5108x + 7.66$	0.2942
Rokytnice	$y = -0.3483x + 126.67$	0.1130	$y = -0.0458x - 0.69$	0.0015
Měděnec	$y = -0.7227x + 10.84$	0.4270	$y = -0.7271x + 10.91$	0.3995
Modrava	$y = -0.0884x + 135.60$	0.0053	$y = -0.0052x + 0.08$	0.00001

the south compared to the north, and it is confirmed not only by mean values but also by extremes values.

Table 3 shows the descriptive statistics of GGD to date the beginning or end of flowering, and during period of flowering as well. The mean values of GDD to F_{begin} oscillate from 84.8 to 120.7 °C, by F_{end} it is from 150.7 to 230.6 °C and by period of flowering values are between 59.0 and 113.9 °C. Stations in warm region W2 (according to Quitt's classification (Tolasz et al. 2007) have the highest values of GDD in all three parameters; on the other side, stations in cold region C7 have the lowest values. But even though the Modrava station is the highest located phenological station in the Czech Republic, 1102 m asl, it does not have the lowest values of GDD. The range of variation coefficient's values in F_{begin} , F_{end} , and F_{period} are subsequent from 23.9 to 43.1, from 20.2 to 43.2, and from 30.0 to 82.7.

The location of stations in the south part of the Czech Republic plays an important role in the phenophase onset and duration of flowering even though the Czech Republic is a small country with the area of 78,865 km² in Central Europe.

Subsequent charts in (Fig. 4) illustrate the linear trend of deviations from average 1991–2019 at 9 stations in F_{begin} and F_{end} . The highest difference is between Modrava (southern-west part of the Czech Republic) and Měděnec (northern-west part of the Czech Republic) station. Coefficients of determination (Table 4) are very low at Modrava and Lednice stations. On the other side, the highest coefficients of determination are at Měděnec, Březina, and Český Rudolec stations.

Table 4. Linear regression equations and coefficients of determination (link to Fig. 4) stations are listed by altitude.

Following the previous charts, since 1991, the timing of both the phenological phases of *Betula pendula* have advanced significantly to an earlier time (Table 5). The most pronounced shifts were detected in F_{begin} and F_{end} at Měděnec station – 7.0 days per decade on average, it means more than 20 days in nearly 30 years' period. The time of flowering shortens, the highest shortening was found at Rokytnice station (–3.8 days per decade on average). Only at Měděnec, Chřibská, and Lednice stations are nearly the same. It is interesting that the GDD have been found in both trends – decreasing or increasing. For example, just at the

Table 5 Linear trends for *Betula pendula* at individual phenological stations during the period 1991–2019 (Per) and also for decade (Dec). GDD 1 – GDD to F_{begin} , GDD 2 – GDD to F_{end} , GDD 3 – GDD during period of flowering (F_{period}), stations are listed by altitude

	F_{begin}		F_{end}		F_{period}		GDD 1		GDD2		GDD3	
	Dec	Per	Dec	Per	Dec	Per	Dec	Per	Dec	Per	Dec	Per
Lednice	–1.7	–5.0	–2.0	–5.7	–0.2	–0.7	–8.9	–25.9	–16.3	–47.3	–7.4	–21.4
Běleč	–4.2	–12.2	–3.0	–8.6	–1.3	–3.6	–1.9	–5.4	–5.6	–16.1	–3.7	–10.7
Chřibská	–5.6	–16.4	–5.6	–16.2	–0.1	–0.2	9.0	26.1	23.8	69.0	14.8	42.9
Březina	–4.8	–14.0	–4.1	–11.9	–0.2	–2.1	–5.4	–15.6	–9.1	–26.4	–3.7	–10.8
Český Rudolec	–3.2	–9.3	–2.5	–7.9	–0.7	–2.1	–6.9	–20.0	–10.1	–29.3	–3.2	–9.3
Brandov	–4.2	–12.2	–4.9	–14.3	–0.7	–1.9	13.9	40.2	17.4	50.3	3.5	10.1
Rokytnice	–5.9	–17.0	–0.4	–1.3	–3.8	–11.0	3.1	8.8	–18.5	–53.7	–21.6	–62.6
Měděnec	–7.0	–20.2	–7.0	–20.4	0.0	0.1	11.1	32.1	16.9	48.9	8.8	16.8
Modrava	–0.9	–2.5	0.0	0.1	–0.8	–2.2	–11.3	–32.9	–19.0	–55.2	–7.3	–21.1

Table 6 Linear trends per decade for mean air temperature (°C) in period 1991–2019, stations are listed by altitude

	Time period	Lednice	Běleč	Chřibská	Březina	Český Rudolec	Brandov	Rokytnice	Měděnec	Modrava
Temperature (°C)	March	0.38*	0.42**	0.24*	0.52*	0.41**	0.18	0.27	0.34**	0.22
	April	0.75**	0.74**	0.66**	0.99***	0.93***	0.65**	0.60**	0.77**	0.91***
	May	0.08	0.02	0.17	0.40*	0.16	0.14	0.02	0.34**	0.03
	Year	0.42**	0.47**	0.40**	0.63**	0.54**	0.39*	0.31	0.53**	0.33*

Notes

***significant trend at $\alpha = 0.050$.**significant trend at $\alpha = 0.010$ *significant trend at $\alpha = 0.001$

Měděnec station, the trend in GDD is higher, also at Brandov and Chřibská stations. The results show that the highest increasing of GDD is in the north; on the other hand, the highest decreasing of GDD is in the south.

In Table 6 are the given linear trends per decade for mean air temperature in March, April, May, and in a year. The significant change occurred in April at Březina, Český Rudolec, and Modrava stations nearly 1 °C per decade. It is interesting that the highest change in May is at Měděnec station as well as per year is also high. The highest change per year is at Březina station.

The following charts (Fig. 5) show dependence of onset day (F_{begin} and F_{end}) or number of days during flowering and GDD. F_{begin} and F_{end} is the highest dependence by Rokytnice, Chřibská, Brandov, Měděnec, and Modrava stations, and by period of flowering, the highest coefficient of determination is by Modrava, Rokytnice, and Měděnec stations. We have also calculated the dependence of individual stations on GDD to a fixed date – April 20 (comparison with timing of the beginning of flowering) and April 30 (comparison with timing of the end of flowering). Coefficients of determination both to F_{begin} , F_{end} , and fixed date are mentioned in Table 7. The values of coefficients of determination are very similar at individual stations and confirm our results.

The values of Pearson's correlation coefficient calculated for GDD and the mean of F_{begin} and F_{end} onset or mean period of flowering (Table 8) showed the temporal development of

this relationship. All values are positive; most stations have higher values by F_{end} than by F_{begin} . The extremely small value of Pearson's correlation coefficient is by F_{begin} at Lednice station (0.061), the highest values are by flowering at Modrava, Rokytnice, and Měděnec stations (0.846; 0.796, and 0.691, respectively), and by F_{end} (0.690; 0.711, and 0.456, respectively).

Discussion

The principal finding of this study was that phenological phases connected with flowering of *Betula pendula* have advanced in timing progressively. During each decade (since 1991), the stages of *Betula pendula* exhibited variable phenological development to warming conditions during the spring. Luomajoki (1999) found out that the timing of the male flowering of birches may vary in Scandinavia from year to year within a range of several weeks. Poikolainen et al. (2016) examined that Finland has high annual variation in phenological development depending on the dominant air currents which causes significant fluctuations between the years, including in the timing of spring phenophases, and birch as well.

The difference in the rate of shifts were between -0.9 and -7.0 d per decade by F_{begin} , from 0.0 to -7.0 d per decade by F_{end} , and -3.8 to -0.2 d per decade by flowering period. The main period of beginning of flowering falls in the third decade

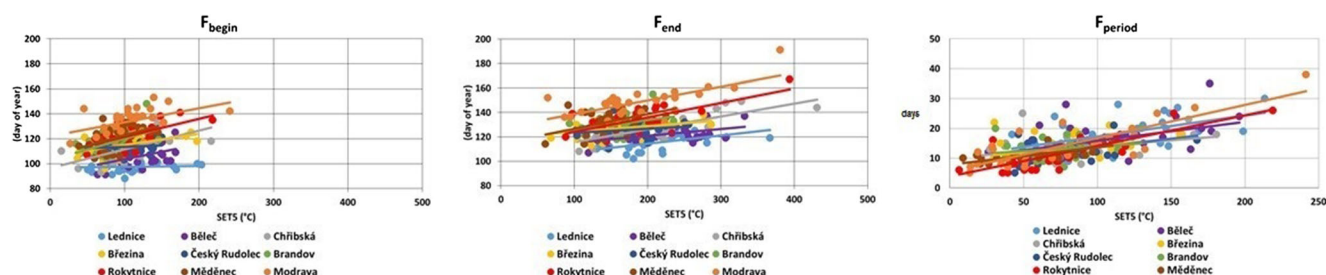
**Fig. 5** Relations between GDD and F_{begin} , F_{end} , and F_{period}

Table 7 Coefficients of determination (link to Fig. 5), stations are listed by altitude

	F _{begin}	April 20	F _{end}	April 30
Lednice	0.0037	0.0076	0.2670	0.1888
Běleč	0.1674	0.1673	0.1802	0.1908
Chřibská	0.3262	0.4193	0.5842	0.5204
Březina	0.2369	0.2575	0.1401	0.1175
Český Rudolec	0.0154	0.0691	0.0382	0.0115
Brandov	0.2255	0.2784	0.1050	0.1881
Rokytnice	0.4062	0.3155	0.5050	0.5191
Měděnec	0.1771	0.2486	0.2078	0.2401
Modrava	0.2038	0.3685	0.4836	0.4584

of April and half of May. D'Amato et al. (2007) mentioned that birch (*Betula*) is the most allergenic pollen tree in northern, central, and eastern Europe. The main flowering period usually starts at the end of March, and in central and eastern Europe, from the beginning to mid-April. Going northward, the flowering season starts depending on the latitude. Emberlin et al. (2002) found out a current trend toward earlier starts of birch pollen season in some parts of Europe. Our results showed that latitude plays a very important role, not only altitude (altitude is an important parameter, which was used in GIS method). Jato et al. (2002) also revealed in their research on *Betula* phenology in Galicia (north-western Spain) and addressed differences in phenological behavior due to a number of environmental factors. The onset of birch pollen season in mountain area is associated with daily average temperature in April (increasing trend); the same have confirmed Yli-Panula et al. (2009) in their analysis of airborne *Betula* pollen in Finland in a 31-year perspective.

Our principal goal was also to compare the phenological response of *Betula pendula* to temperature (GDD since January 1 to phenophase onset). Many authors used a common way to determine the relation between timing of phenological process and climate – to find a correlation between mean temperature during a pre-defined period and the start of the process (e.g., Spieksma et al. 1995). Jato et al. (2007) used similar method as we did, TSUM-GDD. Their results indicate that temperature is able to explain a large part of the variability observed. As we found out, the difference is between north and south, warm and cold regions. The variations in timing of spring phenophases in different parts of Europe

are connected with the weather conditions. The timing of spring phenophases is mainly regulated by temperature, it is also confirmed, e.g., by Caffàra and Donnelly (2011). Ziska et al. (2019) revealed in their findings that the ongoing increase in temperature extremes ($T_{\max}$ and $T_{\min}$) might already be contributing to extended seasonal duration and increased pollen load for multiple aeroallergenic pollen taxa in diverse locations across the northern hemisphere. Zhang et al. (2014) found out in their study that the changes of pollen season timing and airborne levels in the USA depend on latitude and are associated with changes of growing degree days, frost free days, and precipitation. van Vliet et al. (2002) realized in their analysis that a temperature threshold above 0 °C is important for relation between date of pollen start and mean air temperature for most species.

This study demonstrated a significant shift of both F_{begin} and F_{end}. These patterns of phenological shifts to earlier times are well-known. For example, Menzel et al. (2006) stated that the stages of *Betula pendula* show significant phenological shifts to earlier times. Nevertheless, some published papers showed no overall change in the onset of birch pollen although there was evidence that response to temperature was non-linear and that a lower asymptotic start of the pollen season may exist (Newnham et al. 2013). But to sum up, our results are broadly consistent with other studies.

Conclusion

The period of *Betula pendula* flowering have advanced in timing progressively, and the stages of *Betula pendula* exhibited variable phenological development to warming conditions during the spring. The difference in the rate of shifts were between 0.9 to – 7.0 d per decade by F_{begin}, from 0.0 to – 7.0 d per decade by F_{end}, and – 3.8 to – 0.2 d per decade by F_{period}. The significant change in mean air temperature occurs in April (nearly 1 °C per decade at some stations). The results also show that the highest increasing of GDD is in the north; on the other hand, the highest decreasing of GDD is in the south. If we sum it up, there is a difference in *Betula* beginning and end of flowering between the northern and southern part of the country.

The extremely significant change has been detected at Měděnec station in the north-eastern part of the Czech Republic.

Table 8 Pearson's correlation coefficient for GDD and F_{begin}, F_{end}, F_{period}, stations are listed by altitude

	Lednice	Běleč	Chřibská	Březina	Český Rudolec	Brandov	Rokytnice	Měděnec	Modrava
GDD–F _{begin}	0.061	0.409	0.571	0.487	0.124	0.475	0.637	0.421	0.390
GDD–F _{end}	0.517	0.425	0.742	0.374	0.196	0.324	0.711	0.456	0.690
GDD–F _{period}	0.525	0.453	0.369	0.367	0.461	0.213	0.796	0.691	0.846

But we realize that other factors also determine the development speed of plants such as precipitation, day length, or North Atlantic oscillation. But in this study, we aimed to find an explanation for the variation of the pollen season by looking at the temperature only. However, phenological observations alone do not suffice to determine the timing of the main birch pollen season because long-distance transport of pollen may greatly affect the timing of the local birch pollen season as this is also mentioned by other authors (e.g., Ranta et al. 2006). Airborne pollen counts do not always match flowering periods (Jato et al. 2007).

The pollen allergy sensitive persons have to be prepared for problems earlier in spring, and there is a real likelihood that they could meet with other allergens (e.g., hornbeam, alder, beech, and other species). Ziello et al. (2012) found out that continental-scale pollen data set reveals an increasing trend in the yearly amount of airborne pollen for many taxa in Europe, which is more pronounced in urban than in semi-rural/rural areas. Climate change may contribute to these changes. And there is a high level of allergenic cross-reactivity between the representative plants of the genera of the order Fagales which comprises three families: Betulaceae, Corylaceae, and Fagaceae (Furlow 1990). But on the contrary, the birch pollen season is shortening at most of the stations. Therefore, one can summarize that global warming and human health are closely connected. Many authors found out (e.g., Frei and Gassner 2008) that due to global warming and because symptoms may appear earlier in the year, people suffering from pollen allergy might face a new unaccustomed situation. Climate change is expected to affect the spatiotemporal patterns of airborne allergenic pollen, which has been found to act synergistically with common air pollutants, such as ozone, to cause allergic disease (e. g., Zhang et al. 2014, Beggs 2016).

Thus, our results indicate that due to global warming symptoms of birch pollen, allergy may appear earlier in the year, but for a shorter period. Therefore, it is necessary to continue climate change research of birch pollen release connected with phenology, pollen data, and other meteorological parameters, such as precipitation or wind to precise the information for public as much as possible.

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References

- Anonymous (2009) Methodical instructions number 10 for phenological stations – wild plants. CHMI, Prague
- Beggs PJ (2015) Environmental allergens: from asthma to hay fever and beyond. *Curr Clim Change Rep* 1:176–184
- Beggs PJ (ed) (2016) Impacts of climate change on allergens and allergic diseases. Cambridge University Press, Cambridge
- Caffara A, Donnelly A (2011) Modelling the timing of *Betula pubescens* budburst. I. Temperature and photoperiod: a conceptual model. *Clim Res* 46:147–157
- Coufal L, Houška V, Reitschlager JD, Valter J, Vráblík T (2004) Phenological atlas, CHMI, 1st edn. p 204 ISBN 80-86690-21-0
- D'Amato G, Cecchi L, Bonini S, Nunes C, Annesi-Maesano I, Behrendt H, Liccardi G, Popov T, van Cauwenberge P (2007) Allergenic pollen and pollen allergy in Europe. *Allergy* 62:976–990. <https://doi.org/10.1111/j.1398-9995.2007.01393.x>
- Emberlin J, Detandt M, Gehrig R, Jaeger S, Nolard N, Rantio-Lehtimäki A (2002) Responses in the start of *Betula* (birch) pollen seasons to recent changes in spring temperatures across Europe. *Int J Biometeorol* 46(4):159–170. <https://doi.org/10.1007/s00484-002-0139-x>
- Frei T, Gassner E (2008) Climate change and its impact on birch pollen quantities and the start of the pollen season an example from Switzerland for the period 1969–2006. *Int J Biometeorol* 52:667–674. <https://doi.org/10.1007/s00484-008-0159-2>
- Furlow JJ (1990) The genera of Betulaceae in the southeastern United States. *Journal of the Arnold Arboretum* 71(1):1–67
- Glickman TS (managing ed.) (2000) Glossary of meteorology, 2nd edn. American Meteorology Society, Boston, p 855 ISBN: 1-878220-34-9
- Jato V, Méndez J, Rodríguez-Rajo FJ, Seijo C (2002) The relationship between the flowering phenophase and airborne pollen of *Betula* in Galicia (N.W. Spain). *Aerobiologia* 18:55–64
- Jato V, Rodríguez-Rajo FJ, Aira MJ (2007) Use of phenological and pollen- production data for interpreting atmospheric birch pollen curves. *Ann Agric Environ Med* 14:271–280
- Kožnarová V, Klabzuba J (2010) Traditional and modern methods in weather and climate evaluation in biological disciplines. Crop Research Institute, Prague
- Luomajoki A (1999) Differences in climatic adaptation of silver birch (*Betula pendula*) and downy birch (*Betula pubescens*) in Finland based on male flowering phenology. *Acta Forest Fenn* 263:1–35
- Meier U (ed) (1997) Growth stages of mono- and dicotyledonous plants. BBCH Monograph. Federal Biological Research Centre for Agriculture and Forestry, Blackwell Wissenschafts-Verlag, Berlin
- Menzel A (2000) Trend in phenological phases in Europe between 1951 and 1996. *Int J Biometeorol* 44:76–81
- Menzel A et al (2006) European phenological response to climate change matches the warming patterns. *Glob Chang Biol* 12:1969–1976. <https://doi.org/10.1111/j.1365-2486.2006.01193x>
- Newnham RM, Sparks TH, Skjoth CA et al (2013) Pollen season and climate: is the timing of birch pollen release in the UK approaching its limit? *Int J Biometeorol* 57:391–400. <https://doi.org/10.1007/s00484-012-0563-5>
- Poikolainen J, Tolvanen A, Karhu J, Kubin E (2016) Seventeen-year trends in spring and autumn phenophases of *Betula pubescens* in a boreal environment. *Int J Biometeorol* 60:1227–1236. <https://doi.org/10.1007/s00484-015-1118-3>
- Ranta H, Kubi E, Siljamo P, Sofiev M, Linkosalo T, Oksanen A, Bondestam K (2006) Long distance pollen transport cause problems for determining the timing of birch pollen season in Fennoscandia by using phenological observations. *Grana* 45(4):297–304. <https://doi.org/10.1080/00173130600984740>
- Smith KR et al (2014) Human health: impacts, adaptation, and co-benefits. In: Field CB, Barros VR, Dokken DJ, Mach KJ, Mastrandrea MD, Bilir TE et al (eds) *Climate Change 2014: Impacts, Adaptation, and Vulnerability Part A: Global and Sectoral Aspects Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, pp 709–754

- Spieksma FTM, Emberlin J, Hjelmroos M, Jager S, Leuschner RM (1995) Atmospheric birch (*Betula*) pollen in Europe: trend and fluctuations in annual quantities and the starting dates of the season. *Grana* 34:51–37
- Štěpánek P (2007) AnClim – software for time series analysis. Department of Geography, Faculty of Natural Science, MU Brno (<http://www.climahom.eu/AnClim.html>)
- Štěpánek P (2008) ProClimDB – software for processing climatological datasets. CHMI, regional office Brno (<http://www.climahom.eu/ProcData.html>)
- Štěpánek, P et al (2012) Methodology of control and homogenization of time series in climatology. CHMI, 1st edn. ISBN 978-80-86690-97-1, p 118
- Tolasz, R et al (2007) Climate atlas of Czechia. Prague: CHMI, 1st edn. ISBN 978-80-86690-26-1, p 255
- van Vliet AJH, Overeem A, De Groot RS, Jacobs AFG, Spieksma FTM (2002) The influence of temperature and climate change on the timing of pollen release in the Netherlands. *Int J Climatol* 22(14): 1757–1767. <https://doi.org/10.1002/joc.820>
- van Vliet AJH, de Groot RS, Bellens Y, Braun P, Bruegger R, Bruns E, Clevers J, Estreguil C, Flechsig M, Jeanneret F, Maggi M, Martens P, Menne B, Menzel A, Sparks T (2003) The European phenology network. *Int J Biometeorol* 47:202–212 <https://doi.org/10.1007/s00484-003-0174-2>
- Yli-Panula E, Fekedulegn DB, Green BJ, Ranta H (2009) Analysis of airborne *Betula* pollen in Finland; a 31-year perspective. *Int J Environ Res Public Health* 6:1706–1723. <https://doi.org/10.3390/ijerph6061706>
- Zhang Y, Bielory L, Georgopoulos PG (2014) Climate change effect on *Betula* (birch) and *Quercus* (oak) pollen seasons in the United States. *Int J Biometeorol* 58:909–919. <https://doi.org/10.1007/s00484-013-0674-7>
- Ziello C, Sparks TH, Estrella N, Belmonte J, Bergmann KC, Bucher E, Brighetti MA, Damialis A, Detandt M, Galán C, Gehrig R, Grewling L, Gutiérrez Bustillo AM, Hallsdóttir M, Kockhans-Bieda MC, de Linares C, Myszkowska D, Páldy A, Sánchez A, Smith M, Thibaudon M, Travaglini A, Uruska A, Valencia-Barrera RM, Vokou D, Wachter R, de Weger LA, Menzel A (2012) Changes to airborne pollen counts across Europe. *PLoS One* 7(4):e34076. <https://doi.org/10.1371/journal.pone.0034076>
- Ziska LH et al (2019) Temperature-related changes in airborne allergic pollen abundance and seasonality across the northern hemisphere: a retrospective data analysis. *The Lancet Planetary Health* 2019 3(3): e124–e131. [https://doi.org/10.1016/S2542-5196\(19\)30015-4](https://doi.org/10.1016/S2542-5196(19)30015-4)

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