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Changes in flowering of birch in the Czech Republic in recent 25 years (1991–2015) in connection with meteorological variables

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Abstract

The paper presents the results of long-term phenological observations of silver birch (*Betula pendula*) during the years 1991–2015 across the phenological network of the Czech Hydrometeorological Institute (CHMI – Český hydrometeorologický ústav). The data assembled over this period were used for identification of timing of generative phenophases associated with pollen release into the air: inflorescence emergence 10%, beginning of flowering 10%, beginning of flowering 50%, beginning of flowering 100%, and end of flowering. The stations are situated at altitudes from 155 m (Doksany) to 1102 m (Modrava). The average timing of beginning of flowering 10% was 8th April (Lednice = lowland station) and 14th May (Modrava = mountain station); the average timing of beginning of flowering 50% was 12th April (Lednice) and 20th May (Modrava); the average timing of beginning of flowering 100% was 18th April (Lednice) and 22nd May (Modrava), and the average timing of end of flowering was 26th April (Lednice) and 28th May (Modrava).

The totals of effective temperatures above 5°C (TS5) and sums of daily precipitation were used as a bio-climatological criterion for assessment of the dependence of phenological phases on meteorological variables. The average sums of TS5 and the average sums of daily precipitation total were as follows: 61.0–80.8°C, 82.8–327.4 mm (inflorescence emergence); 105.2–106.4°C, 85.9–365.2 mm (beginning of flowering 10%); 124.8–130.8°C, 89.8–385.9 mm (beginning of flowering 50%); 144.7–158.6°C, 95.2–390.7 mm (beginning of flowering 100%); and 181.6–223.8°C, 104.7–427.4 mm (end of flowering).

Synoptic situations occurring during interphase intervals were obtained – the most often found synoptic situations were B (stationary trough over Central Europe), Bp (east travelling trough), NEa (northeast anticyclonic situation), Sa (south anticyclonic situation) and SWc2 (southwest cyclonic situation moving northeast to eastwards).

The period of occurrence of birch pollen in the air lasts 52 days on average and the highest concentration was recorded on 23rd April, 2003 – 2606 pollen grains/m^3.

Keywords: birch; phenology; aerobiology; Czech Republic; CHMI; effective temperature; synoptic situation

Introduction

Phenology and aeropalynology are scientific domenes that study different natural phenomena, i.e., seasonal dynamics of vegetative and generative changes of vegetation and the occurrence of pollen in the air. Another question asked is to what extent phenological observations can be helpful for sensitive people in the prediction of airborn allergenic pollen occurence. The fact that phenological phases are becoming earlier is well known (e.g., [1–3]). Changes in plant phenology are considered as one of the most appropriate bio-indicators and are able to provide important information on the impact of ongoing climate changes on plant development [4,5].

As mentioned by Hájková et al. [6], the *Betula pendula* is the most widespread species of the *Betula* (birch) genus in Europe due to its modesty and resistance against severe climate. The phenology of *Betula* has been studied by many researchers (e.g., [7,8]) and these studies were dealing with possible future effects of climate change on different *Betula* species distributed in various regions.

The role of temperature is often dominant as it affects the rates of most biological and chemical processes within the plant body. Accumulated degree days, calculated as the sum of ambient temperatures above a base temperature, provide a measure of biological or thermal time. Recently, several authors have combined aerobiological, phenological and meteorological data to produce equations for forecasting

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spore concentrations; in some cases, these equations account for up to 40% of spore-count variability when the variables with the highest correlation coefficients are included as estimators [9].

The aim of this paper was to assess which meteorological parameters influence the phenological onset of the allergenic *Betula* pollen and to analyze the shifts in the dates of phenophase onset during 1991–2015 in relation to synoptic situations. The specific aim was to statistically analyze available pollen data from the Prague aerobiological station in order to determine the pollen season and its relation to phenophase onset at the closest phenological station.

Material and methods

The Czech Hydrometeorological Institute (CHMI – Český hydrometeorologický ústav) operates a phenological network of wild plants (Fig. 1), following the specific methodology [10] and the *Phenological atlas* [11]. At present, the birch is observed at 25 phenological stations and the following successive phenological phases are observed: sprouting, first leaves (10, 50, 100%), full leaves, inflorescence emergence, beginning of flowering (10, 50, 100%), end of flowering, formation of buds, yellowing of summer leaves, lignification of sprouts, discoloration (yellowing) of autumn leaves (10, 100%), defoliation (10, 100%), ripe fruits. We focused on the phenological phases associated with pollen production (inflorescence emergence, flowering).

We used phenological data on (***i***) inflorescence emergence 10% (IE 10%), (***ii***) beginning of flowering 10% (BF10%), (***iii***) beginning of flowering 50% (BF50%), (***iv***) beginning of flowering 100% (BF100%), and (***v***) end of flowering (EF) of *Betula pendula* – silver birch. The data originated from the phenological archive PHENODATA of the Czech Hydrometeorological Institute. The period of observation was 1991–2015. The dates of occurrence of phenological phases were transformed into the number of days from 1st January (day of the year – DoY) for further analysis.

The detailed phenophase description represents the methodological instruction No. 10 [10]. Patterns and descriptions of phenophases are illustrated in the *Phenological atlas* [11]:

(***i***) Inflorescence emergence: elongation of catkins (male inflorescences) – the catkin is primarily rigid, with bracts pressed close to one another. Then, the catkins most frequently loosen in the upper third, and bend downwards. In the flexural part, the anthers protrude.

(***ii***) Beginning of flowering: the catkins are soft and already open, the anthers are fully visible and some of them open and release pollen simultaneously. The onset of this phenophase is associated with pollen release into the air.

(***iii***) End of flowering: the catkins are already empty, turn dark and dry, separate from the tree and fall onto the ground.

Birch pollen (Fig. 2) is one of the most important allergens – that is why we also counted the number of days between the phenophases, especially between: inflorescence emergence – beginning of flowering 10% – end of flowering, which are very important for allergy-sensitive persons.

The study was carried out at Lednice, in South Moravia (48°48′ N, 16°48′ E, 165 m a.s.l), and at Modrava in South Bohemia, Šumava Mts (49°02′ N, 13°31′ E, 1102 m a.s.l). The Lednice station is situated in the Dyje River basin, in the Lednice Castle Park. The Modrava station is situated in the southern part of the Šumava Mts, in the Vltava River basin.

Meteorological data, daily mean air temperature and precipitation (daily total) for 1991–2015, were obtained from the climatological stations Lednice (48°48′ N, 16°48′ E, 177 m a.s.l) and Churáňov (49°04′ N, 13°37′ E, 1118 m a.s.l).

These data were analyzed using Microsoft Excel; additionally, we used correlation function analysis to identify the main climatic parameters explaining year-to-year variations in phenological series. Climagrams (Fig. 3, Fig. 4) were used to characterize climate conditions. We used a modified Walter–Lieth climagram (e.g., [12–14]) based on the long-term average 1961–2010.

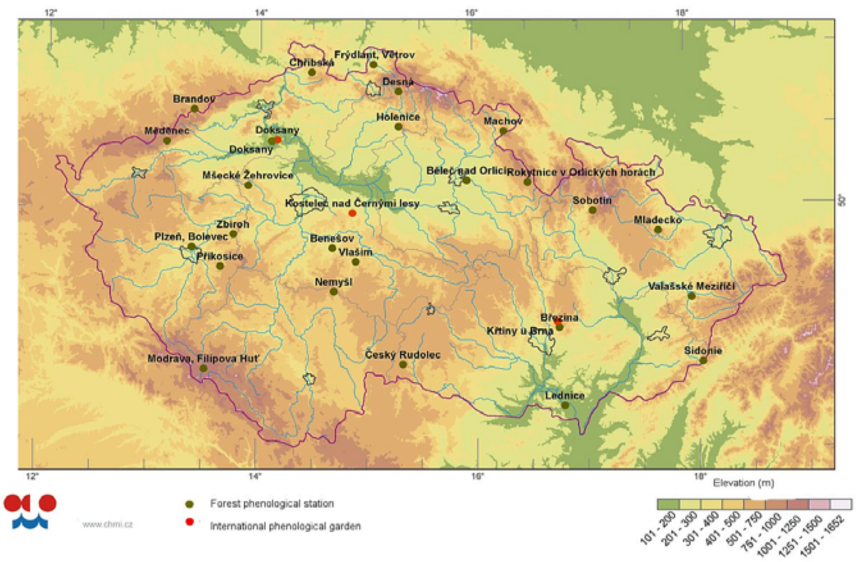


Fig. 1 Map of CHMI phenological stations (status as of 1st January, 2013).

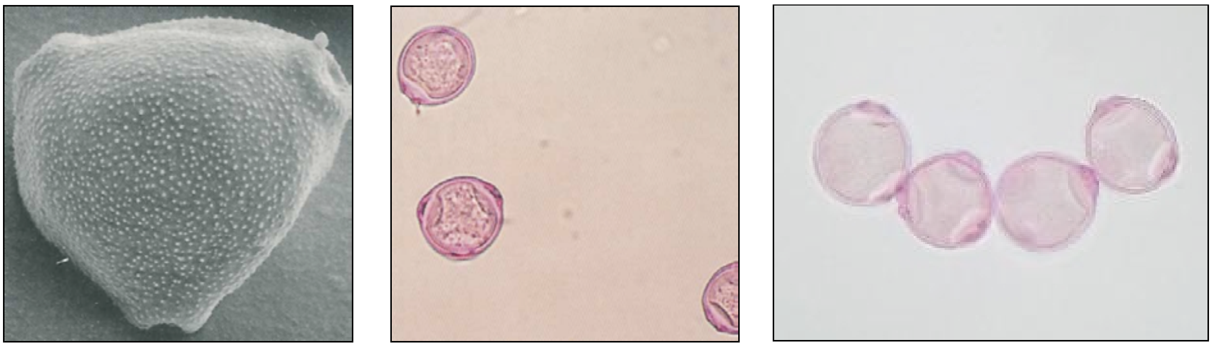


Fig. 2 Birch pollen grains (source: http://www.geog.qmul.ac.uk).

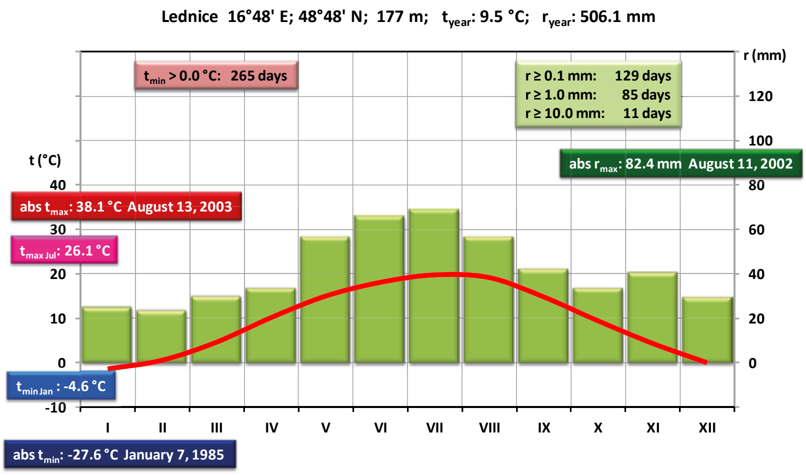


Fig. 3 Climagram for Lednice station. t – average monthly air temperature (°C); r – average monthly precipitation total (mm); t_{year} – average annual air temperature (°C); r_{year} – average annual precipitation total (mm); abs t_{max} – absolute maximum of air temperature; $t_{max\ Jul}$ – average monthly maximum of air temperature of the warmest month; $t_{min\ Jan}$ – average monthly minimum of air temperature of the coldest month; abs t_{min} – absolute minimum of air temperature; t_{min} > 0.0°C – average number of days with air temperature >0.0°C; abs r_{max} – absolute maximum of daily total precipitation; r ≥ 0.1 mm – average number of days with total precipitation ≥0.1 mm; r ≥ 1.0 mm – average number of days with total precipitation ≥1.0 mm; r ≥ 10.0 mm – average number of days with daily precipitation total ≥10.0 mm.

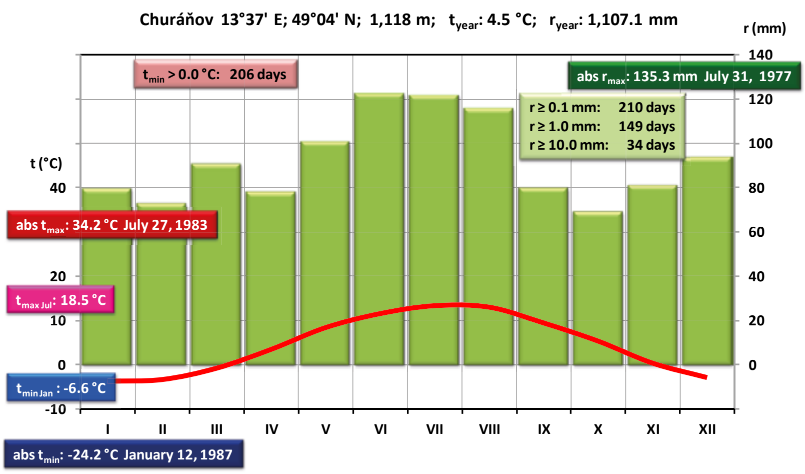


Fig. 4 Climagram for Churáňov station.

The Czech aerobiological network was established in 1992. Currently, all sampling stations (10 at present) use the volumetric suction sampler based on the impact principle, as initially designed by Hirst [15]. Microscopic examination of aerobiological samples is essential for obtaining reliable results; it is also one of the most time-consuming stage of the data collecting process, due to the abundant material sometimes present on sample tapes. The weekly pollen counts are sent to the EAN (European Aeroallergen Network), located in Vienna. For the purpose of this paper, only data (counts of birch pollen grains) from the Prague aerobiological station (14°27′ N, 50°03′ E, 278 m a.s.l) were used, as unfortunately we were unable to obtain data from other aerobiological stations. The sampler is situated on the roof of the NIPH (The National Institute of Public Health) building in Prague. Aerobiological data for the period from 2001 to 2014 were obtained.

Synoptic situation was assessed according to the Brádka classification [16–18] presented on http://www.chmi.cz. Types of synoptic situations are given in Tab. 1.

To provide a temporal and spatial pattern of phenophase onset over the whole Czech Republic, the data were converted into maps (the mean dates of phenophase onset for the period 1991–2010).

The maps were processed with using geographic information systems (Application Clidata-GIS). The mean dates of phenophase onset from the period 1991–2010 were used as the input data. The maps use a horizontal resolution of 500 meters with reference to altitude [the method of local linear regression (LLR) between the measured or calculated value and the digital relief model]. The regression coefficients were calculated for each station, based on the data from neighboring stations and in accordance with the least squares method. The coefficients were subsequently interpolated into the space model, and the space distribution of the specific element was calculated by means of map algebra and linear equations.

In total, data from 44 stations lacated from 155 m a.s.l (Doksany – Polabská nížina) to 1102 m a.s.l (Filipova Huť – Šumava Mts) were used to create the maps. The maps had been drawn before the CHMI phenological network was reduced; therefore there are only 25 phenological stations from 1st January 2013. The data form Lednice (165 m a.s.l) and Modrava (1102 m a.s.l) are described in detail in the statistical results. These stations were selected for the evaluation due to different climatological conditions at either of these sites.

Results

The onset and duration of phenological phases of birch differed considerably between years.

The statistical data for the selected stations are shown in Fig. 5 and Fig. 6 by boxplots (minimum, lower quartile, median, upper quartile and maximum) and other statistical parameters are given in Tab. 2–Tab. 6.

Standard deviation, variance and variation range are higher at the Modrava station. A comparison of particular periods (1991–2000 and 2001–2010) is shown in Tab. 7. Both stations report earlier phenophase onset in the second decade and the differences are higher at Modrava station, i.e., in the mountains. Fig. 7–Fig. 9 illustrate the mean phenophase onset in the Czech Republic in the period 1991–2010.

Deviations in the phases of inflorescence emergence, beginning of flowering 10%, and end of flowering from the long-term average (1991–2015) at both stations are shown in Fig. 10–Fig. 12, while polynomial equations including R^2 are contained in Tab. 8. At the Lednice station, the highest positive deviations (i.e., later phenophase onset) were reported in 1996 (inflorescence emergence and beginning of flowering 10%) and 1991 (end of flowering), whereas at the Modrava station in 2010 (all three phenophases in the same year and

Tab. 1 Types of synoptic situations.

A	Stationary anticyclone over Central Europe	**NWa**	Northwest anticyclonic situation
Ap1	Travelling anticyclone from SW to NE	**NWc**	Northwest cyclonic situation
Ap2	Travelling anticyclone from W to E	**Sa**	South anticyclonic situation
Ap3	Travelling anticyclone from NW to SE	**SEa**	Southeast anticyclonic situation
Ap4	Travelling anticyclone from N to S	**SEc**	Southeast cyclonic situation
B	Stationary trough	**SWa**	Southwest anticyclonic situation
Bp	East travelling trough	**SWc1**	Southwest cyclonic situation moving north to northeastwards
C	Cyclone over Central Europe	**SWc2**	Southwest cyclonic situation moving northeast to eastwards
Cv	Upper-air cyclone	**SWc3**	Southwest cyclonic situation with frontal zone shifted southwards
Ea	East anticyclonic situation	**Vfz**	Frontal zone entrance
Ec	East cyclonic situation	**Wa**	West anticyclonic situation
Nc	North cyclonic situation	**Wal**	West anticyclonic situation of a summer type
NEa	Northeast anticyclonic situation	**Wc**	West cyclonic situation
NEc	Northeast cyclonic situation	**Wcs**	West cyclonic situation with southern track of cyclones

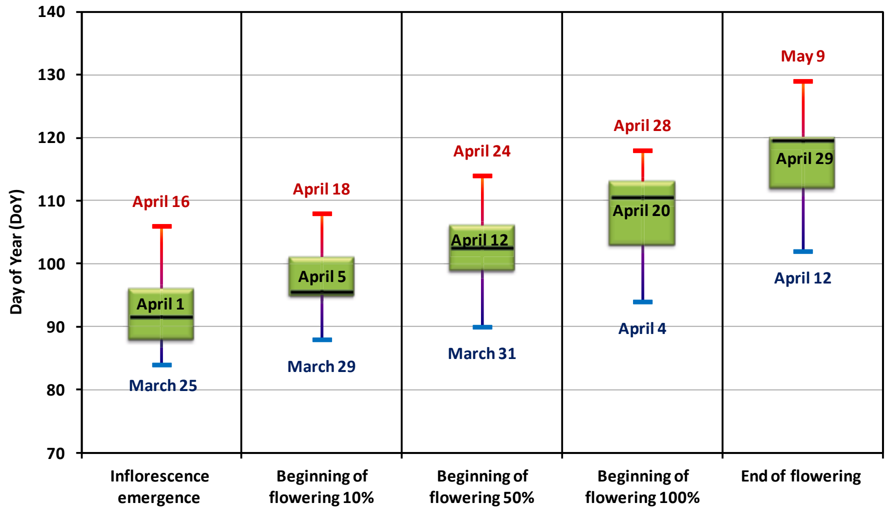


Fig. 5 Statistical characteristics of phenophases (Lednice station).

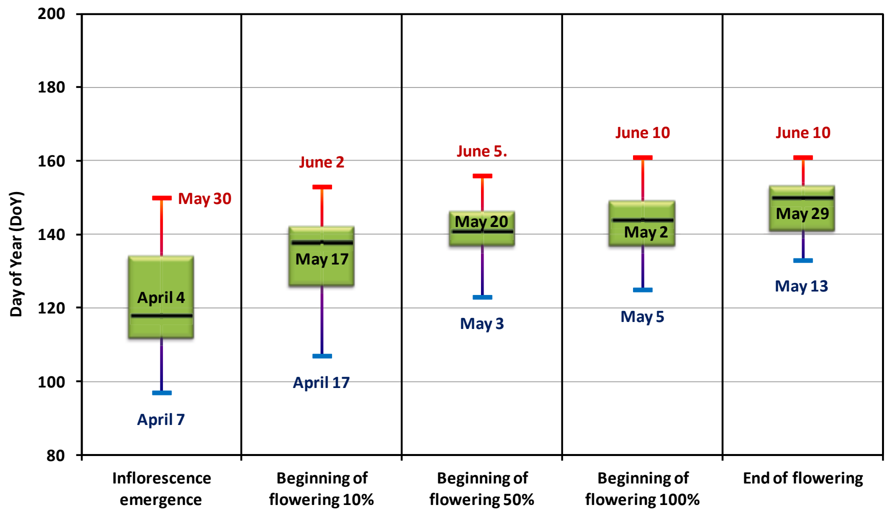


Fig. 6 Statistical characteristics of phenophases (Modrava station).

Tab. 2 Phenophase – inflorescence emergence (statistical results).

Station	Average	Standard deviation	Variance	10% percentile	90% percentile	Variation range	Average – median
Lednice	April 2	5.9	34.4	March 26	April 11	22	1
Modrava	May 1	14.0	194.7	April 14	May 20	53	4

Tab. 3 Phenophase – beginning of flowering 10% (statistical results).

Station	Average	Standard deviation	Variance	10% percentile	90% percentile	Variation range	Average – median
Lednice	April 8	4.9	24.0	April 3	April 15	20	3
Modrava	May 14	10.7	114.4	May 2	May 25	76	−3

Tab. 4 Phenophase – beginning of flowering 50% (statistical results).

Station	Average	Standard deviation	Variance	10% percentile	90% percentile	Variation range	Average – median
Lednice	April 12	5.3	27.9	April 7	April 18	24	0
Modrava	May 20	8.3	68.1	May 7	May 30	33	0

Tab. 5 Phenophase – beginning of flowering 100% (statistical results).

Station	Average	Standard deviation	Variance	10% percentile	90% percentile	Variation range	Average – median
Lednice	April 18	6.1	37.4	April 10	April 25	24	−2
Modrava	May 22	9.1	83.2	May 8	June 2	36	−1

Tab. 6 Phenophase – end of flowering 100% (statistical results).

Station	Average	Standard deviation	Variance	10% percentile	90% percentile	Variation range	Average – median
Lednice	April 26	6.7	45.0	April 18	May 5	27	−3
Modrava	May 28	7.9	62.2	May 17	June 8	28	−1

Tab. 7 Comparison of particular periods.

	IF		BF10%		BF50%		BF100%		EF	
Period	**Lednice**	**Modrava**	**Lednice**	**Modrava**	**Lednice**	**Modrava**	**Lednice**	**Modrava**	**Lednice**	**Modrava**
1991–2000	Apr 4	May 2	Apr 10	May 18	Apr 14	May 23	Apr 19	May 25	Apr 27	May 30
2001–2010	Apr 2	Apr 22	Apr 7	May 8	Apr 11	May 16	Apr 17	May 18	Apr 25	May 25

IF – inflorescence emergence; BF10% – beginning of flowering 1%; BF50% – beginning of flowering 50%; BF100% – beginning of flowering 100%; EF – end of flowering.

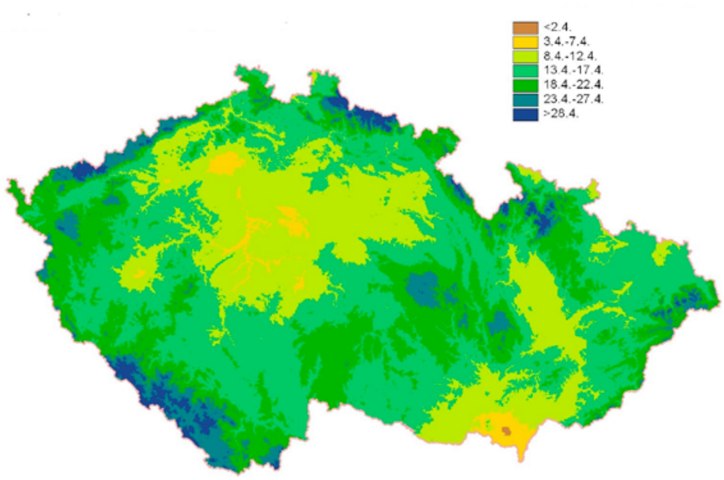


Fig. 7 Inflorescence emergence (source: *Atlas of the phenological conditions in Czechia* [3]).

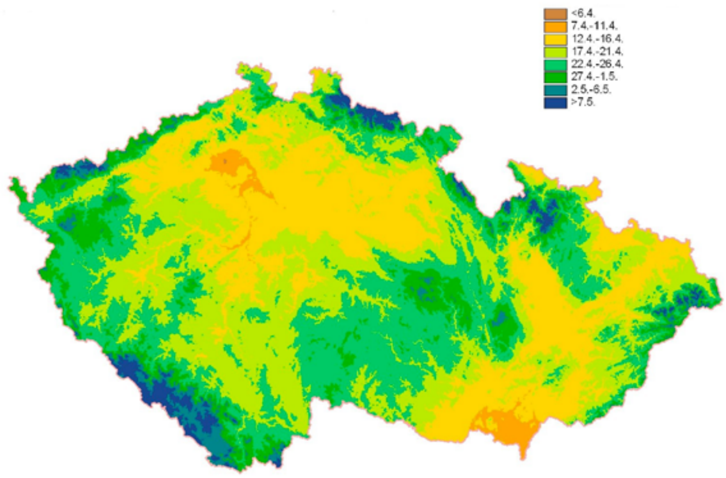


Fig. 8 Beginning of flowering 10% (source: *Atlas of the phenological conditions in Czechia* [3]).

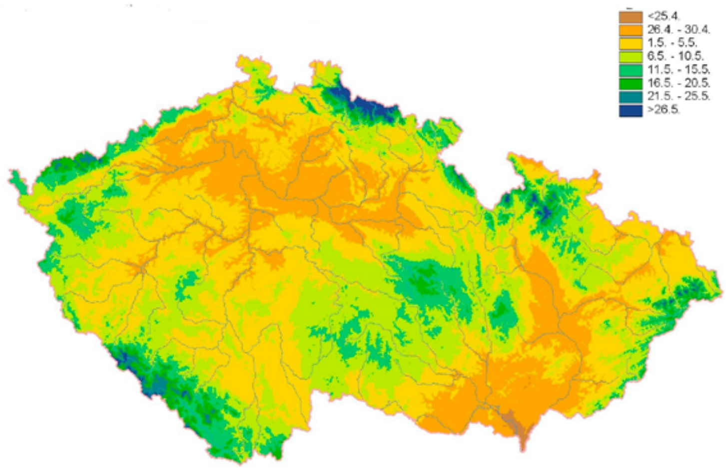


Fig. 9 End of flowering (source: *Atlas of the phenological conditions in Czechia* [3]).

inflorescence emergence was delayed by even 29 days). The highest negative deviations (i.e., earlier phenophase onset) were in 1999 and 2014 at the Lednice station and in 1993 and 2007 at the Modrava station (beginning of flowering 28 days earlier). At the Lednice station, the deviations from the long-term average are much smaller than at the Modrava station. The values of the coefficient of determination are smaller for the Lednice station (all values are very similar), while at the Modrava station the value of R^2 for inflorescence emergence is highest.

We also focused on evaluation of the following interphase intervals:

(***i***) inflorescence emergence – beginning of flowering 10%
(***ii***) beginning of flowering 10% – beginning of flowering 50%
(***iii***) beginning of flowering 50% – beginning of flowering 100%
(***iv***) beginning of flowering 100% – end of flowering
(***v***) beginning of flowering 10% – end of flowering.

Fig. 13, Fig. 14 and Tab. 9–Tab. 15 illustrate the statistical characteristics of the interphases. Standard deviation, variance and variation range are usually higher at the Modrava station, except for the period from beginning of flowering 50% to beginning of flowering 100%. The intervals tended to lengthen, but also to shorten over the study period; it is very variable (Tab. 16).

The sums of effective temperatures and the sums of precipitation (daily total) were calculated for each station according to the representative climatological stations (Lednice and Churáňov) from the beginning of the year to the onset of the particular phenophase. The average sums of effective temperatures and daily precipitation, including other statistical characteristics, are given in Tab. 17 and Tab. 18.

The variation coefficients are very small for all the phenophases and at both stations. The average values of the

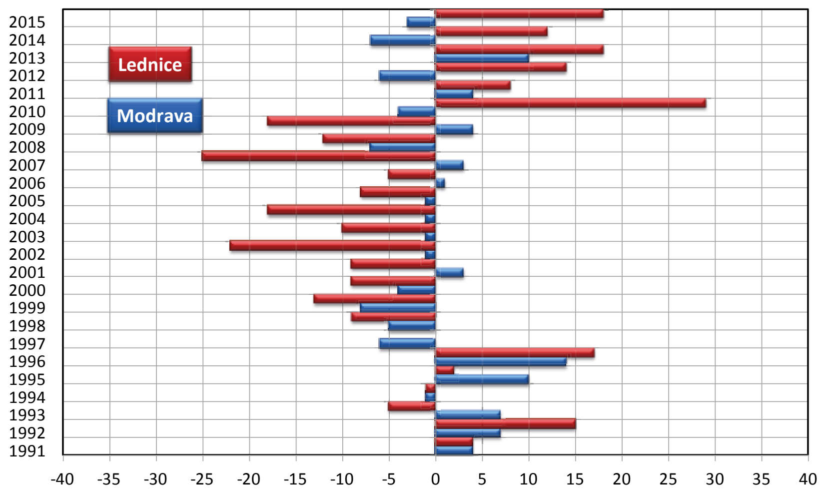


Fig. 10 Deviations in the onset of the inflorescence emergence phenophase at the Lednice and Modrava stations.

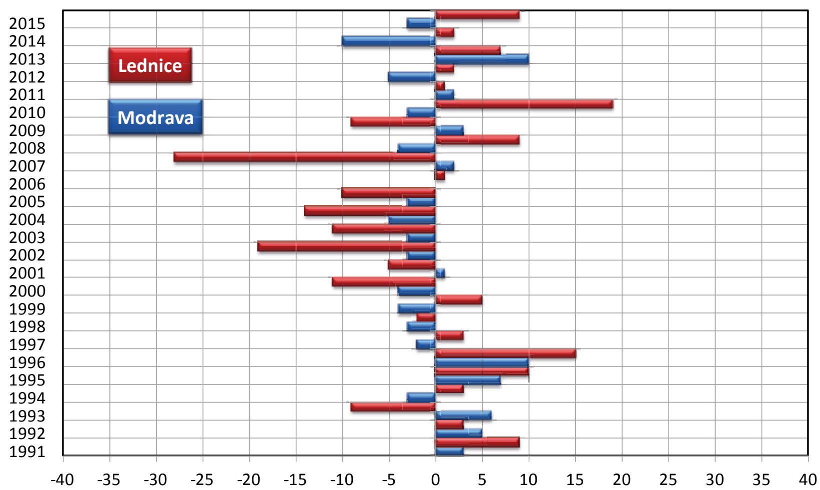


Fig. 11 Deviations in the onset of the beginning of flowering 10% phenophase at the Lednice and Modrava stations.

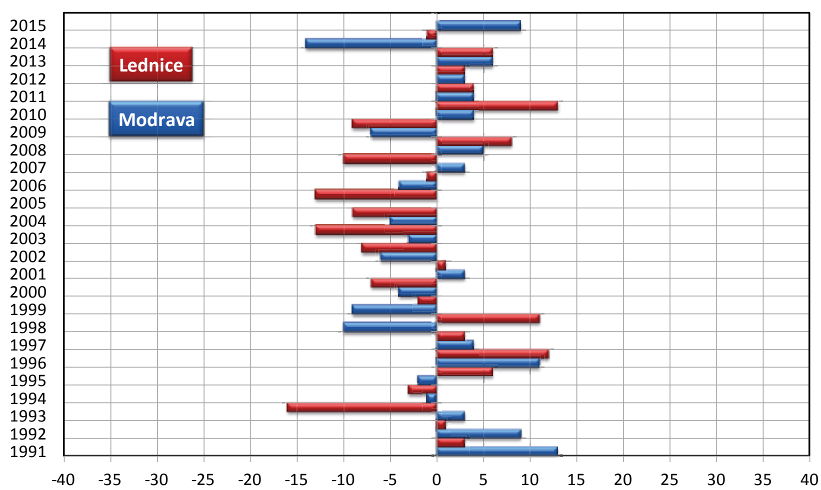


Fig. 12 Deviations in the onset of the end of flowering phenophase at the Lednice and Modrava stations.

Tab. 8 Polynomial equations (6th degree).

Phenophase	Station	Polynomial equation	R^2
Inflorescence emergence	Lednice	$y = -1E\text{-}05x6 + 0.0012x5 - 0.0388x4 + 0.6195x3 - 4.8296x2 + 15.267x - 8.1408$	0.2669
	Modrava	$y = 4E\text{-}06x6 - 0.0005x5 + 0.0187x4 - 0.2851x3 + 1.7453x2 - 5.0657x + 10.087$	0.6026
Beginning of flowering 10%	Lednice	$y = 3E\text{-}07x6 + 1E\text{-}05x5 - 0.0022x4 + 0.0767x3 - 0.9854x2 + 3.9966x - 0.1672$	0.2905
	Modrava	$y = 5E\text{-}05x6 - 0.0044x5 + 0.1325x4 - 1.8792x3 + 12.464x2 - 34.739x + 32.617$	0.4974
End of flowering	Lednice	$y = 2E\text{-}05x6 - 0.0017x5 + 0.0493x4 - 0.6863x3 + 4.8101x2 - 17.089x + 26.548$	0.3523
	Modrava	$y = 5E\text{-}05x6 - 0.0043x5 + 0.1333x4 - 1.9604x3 + 13.577x2 - 38.764x + 31.08$	0.5366

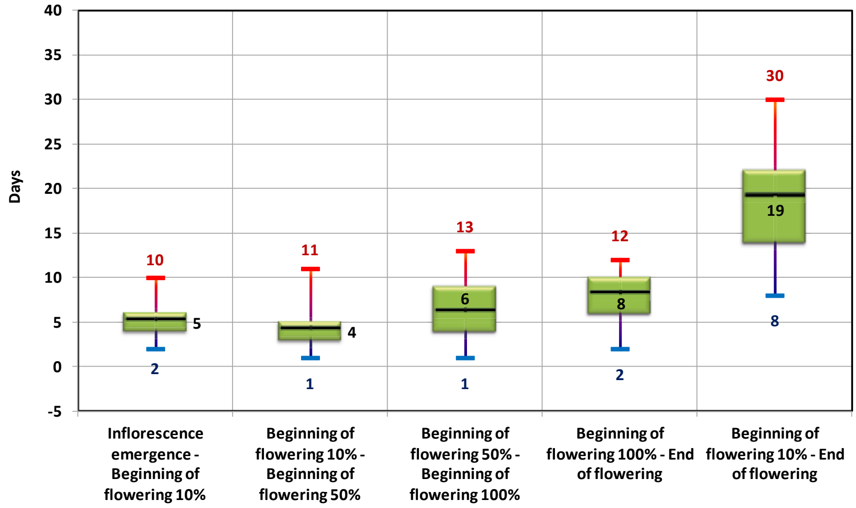


Fig. 13 Statistical characteristics of interphase intervals (Lednice station).

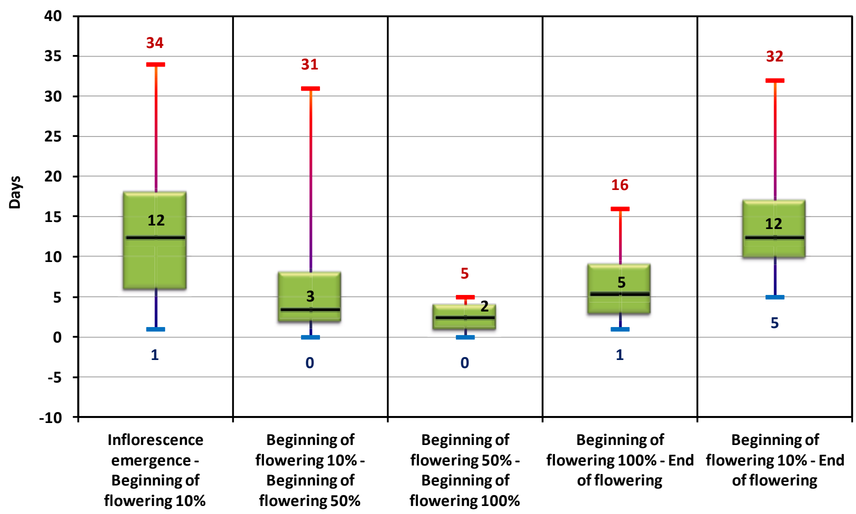


Fig. 14 Statistical characteristics of interphase intervals (Modrava station).

Tab. 9 Average number of days between phenophases (difference between mean dates).

Station	Inflorescence emergence – beginning of flowering 10%	Beginning of flowering 10% – end of flowering	Inflorescence emergence – end of flowering
Lednice	5	19	24
Modrava	13	14	27

Tab. 10 Inflorescence emergence – beginning of flowering 10%.

Station	Average	Standard deviation	Variance	Variation range
Lednice	5	2.2	4.7	8
Modrava	13	8.7	75.3	33

Tab. 11 Beginning of flowering 10% – beginning of flowering 50% (statistical results).

Station	Average	Standard deviation	Variance	Variation range
Lednice	4	2.2	5.0	10
Modrava	6	6.9	47.1	31

Tab. 12 Beginning of flowering 50% – beginning of flowering 100% (statistical results).

Station	Average	Standard deviation	Variance	Variation range
Lednice	6	3.0	8.9	12
Modrava	2	1.5	2.1	5

Tab. 13 Beginning of flowering 100% – end of flowering (statistical results).

Station	Average	Standard deviation	Variance	Variation range
Lednice	8	2.6	6.8	10
Modrava	6	3.8	14.8	15

Tab. 14 Beginning of flowering 10% – end of flowering (statistical results).

Station	Average	Standard deviation	Variance	Variation range
Lednice	19	5.7	32.8	22
Modrava	14	6.5	41.8	27

Tab. 15 Inflorescence emergence – end of flowering (statistical results).

Station	Average	Standard deviation	Variance	Variation range
Lednice	24	6.5	42.8	24
Modrava	27	11.1	123.7	38

Tab. 16 Changes in interphase intervals in particular periods.

	IF–BF10%		BF10%–BF50%		BF50%–BF100%		BF100%–EF		BF10%–EF		IF–EF	
	Lednice	Modrava	Lednice	Modrava	Lednice	Modrava	Lednice	Modrava	Lednice	Modrava	Lednice	Modrava
1991–2000	5.7	15.5	4.1	5.3	5.6	2.3	8.2	4.6	17.9	12.2	23.6	27.7
2001–2010	4.9	16.1	4.7	8.1	6.1	1.4	7.7	7.1	18.5	16.6	23.4	32.7

IF – inflorescence emergence; BF10% – beginning of flowering 10%; BF50% – beginning of flowering 50%; BF100% – beginning of flowering 100%; EF – end of flowering.

Tab. 17 Statistical characteristics of effective temperature above 5°C (TS5) to phenophase onset.

	IF		BF10%		BF50%		BF100%		EF	
	Lednice	Modrava	Lednice	Modrava	Lednice	Modrava	Lednice	Modrava	Lednice	Modrava
Average	80.8	61.0	105.2	106.4	124.8	130.8	158.6	144.7	223.8	181.6
Median	78.6	43.3	101.2	113.9	118.2	135.5	158.0	145.8	226.0	165.6
Upper q.	52.0	19.0	86.9	77.9	100.4	101.1	131.2	106.8	187.1	152.4
Lower q.	100.6	88.6	118.3	139.9	145.0	156.8	172.0	171.4	255.8	214.7
Minimum	36.0	9.3	48.3	16.7	66.5	21.0	80.7	49.1	143.9	59.5
Maximum	170.1	163.1	201.7	173.7	243.1	220.5	292.8	262.7	371.9	321.2
10% perc	43.4	16.8	62.4	49.9	72.8	65.2	101.9	70.3	164.1	99.2
90% perc.	111.9	142.4	158.0	159.3	181.6	185.9	209.3	213.3	272.9	269.5
Stand. dev.	31.1	49.9	36.2	41.8	41.8	47.1	48.7	52.4	51.0	65.7
Var. coeff.	0.4	0.8	0.3	0.4	0.3	0.4	0.3	0.4	0.2	0.4

IF – inflorescence emergence; BF10% – beginning of flowering 10%; BF50% – beginning of flowering 50%; BF100% – beginning of flowering 100%; EF – end of flowering.

Tab. 18 Statistical characteristics of effective temperature above 5°C (TS5) to phenophase onset.

	IF		BF10%		BF50%		BF100%		EF	
	Lednice	Modrava	Lednice	Modrava	Lednice	Modrava	Lednice	Modrava	Lednice	Modrava
Average	82.8	327.4	85.9	365.2	89.8	385.9	95.2	390.7	104.7	427.4
Median	86.2	332.8	86.8	384.5	89.2	397.9	96.9	401.7	115.9	447.4
Upper q.	48.7	281.9	57.8	317.6	58.6	335.6	61.4	338.9	68.8	348.7
Lower q.	106.4	380.0	119.2	428.8	119.2	446.3	127.3	449.1	132.0	480.5
Minimum	18.0	165.2	18.3	207.1	19.5	217.5	23.0	217.5	32.0	217.5
Maximum	179.2	501.1	179.2	578.9	179.2	578.9	179.2	625.2	180.7	660.2
10% perc	31.6	236.7	33.4	260.3	37.7	271.1	38.5	274.3	52.7	325.8
90% perc.	140.8	397.4	141.5	441.1	153.0	471.7	154.6	474.7	158.5	542.9
Stand. dev.	42.1	75.3	42.0	82.2	43.8	85.8	43.7	90.0	41.9	101.5
Var. coeff.	0.5	0.2	0.5	0.2	0.5	0.2	0.5	0.2	0.4	0.2

IF – inflorescence emergence; BF10% – beginning of flowering 10%; BF50% – beginning of flowering 50%; BF100% – beginning of flowering 100%; EF – end of flowering.

sums of effective temperatures are similar at both stations (inflorescence emergence, beginning of flowering 100%, and end of flowering show smaller values at the Modrava station), while on the other hand the average values of the sums of daily precipitation are much higher at the Modrava station. At the Modrava station, the correlation coefficients (Tab. 19) between phenophase onset and effective temperatures above 5°C are positive, and the highest value is for inflorescence emergence (0.667). As regards the sum of daily precipitation total, the coefficients are negative for inflorescence emergence and beginning of flowering 10%, and positive for beginning of flowering 50%, 100% and end of flowering. At the Lednice station, the correlation coefficients are negative for inflorescence emergence and beginning of flowering 10%, whereas the other phenophases show positive correlation coefficients.

Tab. 19 Correlation coefficients between IF, BF10%, EF and climatic variables.

	IF	BF10%	BF50%	BF100%	EF
Lednice					
Effective temperature 5°C	−0.298	−0.294	0.144	0.201	0.196
Precipitation	−0.298	−0.294	0.161	0.103	0.196
Modrava					
Effective temperature 5°C	0.667	0.342	0.149	0.287	0.361
Precipitation	−0.142	−0.021	0.149	0.010	0.174

IF – inflorescence emergence; BF10% – beginning of flowering 10%; BF50% – beginning of flowering 50%; BF100% – beginning of flowering 100%; EF – end of flowering.

Tab. 20 The occurrence of synoptic situations between phenophases in the period 1991–2015.

	IF–BF10%		BF10%–BF50%		BF50%–BF100%		BF100%–EF	
Situation	**Lednice**	**Modrava**	**Lednice**	**Modrava**	**Lednice**	**Modrava**	**Lednice**	**Modrava**
A	8	2	3	0	3	2	0	6
AP_1	4	6	1	3	2	0	5	5
Ap_2	3	10	1	3	3	0	7	2
Ap_3	0	5	2	4	0	0	10	0
Ap_4	1	0	0	0	0	0	1	0
B	5	23	12	8	16	4	30	14
Bp	12	27	6	10	8	1	14	14
C	3	8	5	6	12	3	14	3
Cv	0	8	0	0	2	0	5	0
Ea	6	9	3	2	4	1	10	6
Ec	3	12	4	5	8	1	8	5
Nc	0	4	7	7	4	1	1	3
NEa	5	31	2	7	4	1	1	15
NEc	3	17	7	10	11	0	5	8
NWa	8	6	5	3	1	0	1	0
NWc	11	13	3	8	10	0	0	3
Sa	3	12	3	4	2	5	12	2
SEa	7	19	3	4	5	0	12	6
SEc	0	22	0	6	4	0	3	4
SWa	1	5	1	1	0	0	8	2
SWc_1	7	12	0	3	1	2	10	2
SWc_2	1	15	6	9	0	4	4	8
SWc_3	7	20	2	2	3	1	10	5
Vfz	7	11	1	5	0	1	5	3
Wa	4	2	0	2	4	0	0	2
Wc	8	10	4	4	6	0	2	7
Wcs	0	7	0	2	0	0	6	3

Tab. 21 The occurrence of synoptic situations between phenophases in the period 1991–2015.

Situation	BF10%–BF100%		BF10%–EF		IF–EF	
	Lednice	Modrava	Lednice	Modrava	Lednice	Modrava
A	6	2	6	8	14	10
AP_1	3	3	8	8	12	14
Ap_2	4	3	11	5	14	15
Ap_3	2	4	12	4	12	9
Ap_4	0	0	1	0	2	0
B	28	12	58	26	63	49
Bp	14	11	28	25	40	52
C	17	9	31	12	34	20
Cv	2	0	7	0	7	8
Ea	7	3	17	9	23	18
Ec	12	6	20	11	23	23
Nc	11	8	12	11	12	15
NEa	6	8	7	23	12	54
NEc	18	10	23	18	26	35
NWa	6	3	7	3	15	9
NWc	13	8	13	11	24	24
Sa	5	9	17	11	20	23
SEa	8	4	20	10	27	29
SEc	4	6	7	10	7	32
SWa	1	1	9	3	10	8
SWc_1	1	5	11	7	18	19
SWc_2	6	13	10	21	11	36
SWc_3	5	3	15	8	22	28
Vfz	1	6	6	9	13	20
Wa	4	2	4	4	8	6
Wc	10	4	12	11	20	21
Wcs	0	2	6	5	6	12

An overview of the occurrence of synoptic situations between the phenophases: inflorescence emergence, beginning of flowering 10%, beginning of flowering 50%, beginning of flowering 100% and the end of flowering, is given in Tab. 20 and Tab. 21. The text highlighted in grey color means the occurrence of the maximum situation. Situations are various, alternating. The most often found synoptic situations between phenophase intervals are mentioned below:

(***i***) inflorescence emergence – beginning of flowering 10%: Bp (Lednice station – 12×) and NEa (Modrava station – 31×)
(***ii***) beginning of flowering 10% – beginning of flowering 50%: B (Lednice station – 12×) and Bp (Modrava station – 10×)
(***iii***) beginning of flowering 50% – beginning of flowering 100%: B (Lednice station – 16×) and Sa (Modrava station – 5×)
(***iv***) beginning of flowering 100% – end of flowering: B (Lednice station – 30×) and NEa (Modrava station – 15×)
(***v***) beginning of flowering 10% – beginning of flowering 100%: B (Lednice station – 28×) and SWc2 (Modrava station – 13×)
(***vi***) beginning of flowering 10% – end of flowering: B (Lednice station – 58×; Modrava station – 26×)
(***vii***) inflorescence emergence – end of flowering: B (Lednice station – 63×) and NEa (Modrava station – 54×).

Pressure distribution and circulation over Central Europe in the analyzed synoptic situations within interphases (B: stationary trough over Central Europe; Bp: east travelling trough; NEa: northeast anticyclonic situation; Sa: south anticyclonic situation; SWc2: southwest cyclonic situation moving northeast to eastwards) are presented in Tab. 15a.

The period of occurrence of birch pollen grains in the air lasts 52 days on average in the Prague agglomeration. An overview of airborne pollen in particular years is shown in Tab. 22, Tab. 23, and Fig. 16.

The longest period of the birch pollen season, occurred in 2001 (90 days) and the shortest period was in 2009 (31 days). The beginning of the birch pollen season usually takes place between 9th March and 7th April, while the end of the birch pollen season is usually between 3rd May and 7th June. At the Mšecké Žehrovice station (the closest phenological station to Prague, 50°10′ N, 13°54′ E, 460 m a.s.l), over the same period (2001–2014) flowering of birch begins between 30th March and 24th April (21 days later), and ends between 15th April and 8th May (18 days earlier). At the Lednice station, the beginning of flowering occurs between 29th March and 18th April and end of flowering between 12th April and 1st May. For the Modrava station,

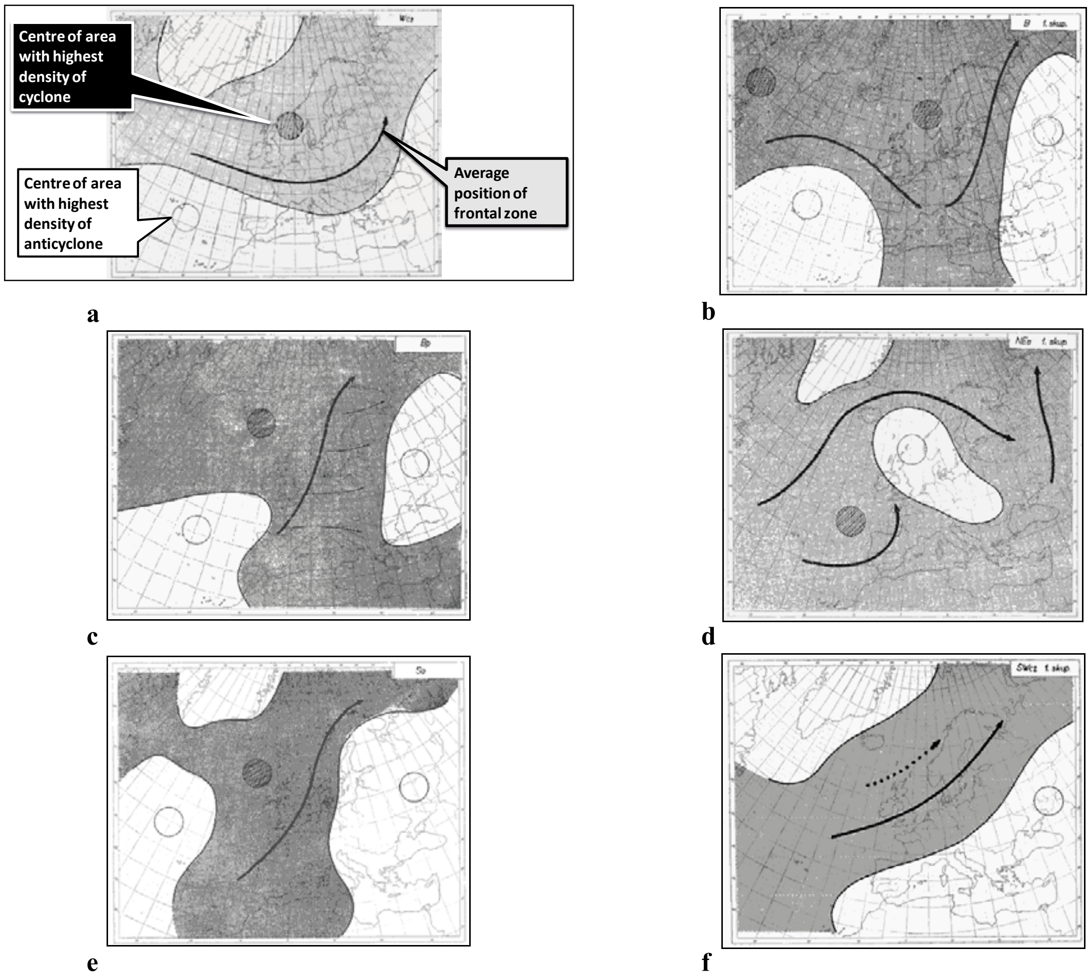


Fig. 15 **a** Illustrative pattern. **b** B: stationary trough over Central Europe. **c** Bp: east travelling trough. **d** NEa: northeast anticyclonic situation. **e** Sa: south anticyclonic situation. **f** SWc2: southwest cyclonic situation moving northeast to eastwards.

Tab. 22 Evaluation of pollen grains in 2001–2014 (statistical results).

	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
Maximum	1209	752	2606 April 23	657	1112	1977 April 22	904	992	715	1764	581	908	798	2046 April 2
Upper q.	5	9	5	16	4	5	12	13	5	23	21	34	6	3
Average	155	143	319	145	139	366	151	220	116	362	108	240	93	250
Median	43	64	52	72	38	79	42	70	24	108	69	151	20	17
Lower q.	181	214	462	174	164	532	279	274	159	365	155	356	45	159
Minimum	1	1	1	2	1	1	2	1	1	2	1	4	2	1
Stand. dev.	256	186	501	181	246	526	212	308	177	521	130	241	191	475

Tab. 23 Duration of birch pollen seasons in Prague.

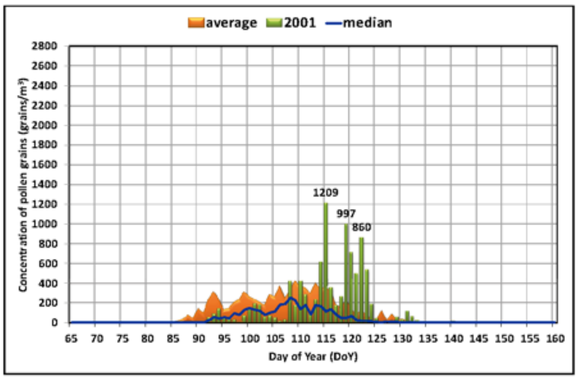
	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
From	April 9	March 18	April 7	March 30	April 4	April 13	March 25	March 24	April 2	April 3	April 2	March 21	March 29	March 17
To	June 7	May 19	May 18	May 9	May 22	May 28	May 13	May 11	May 3	May 9	May 5	May 5	May 24	May 18
Days	90	62	41	39	48	45	49	48	31	36	33	45	56	62

these dates were between 17th April and 2nd June (beginning of flowering 10 %) and 16th May and 10th June (end of flowering). Airborne pollen counts do not always match flowering periods. Airborne *Betula* pollen may be detected prior to and after flowering.

Discussion

The investigations conducted by Hájková et al. [19] and other researchers (e.g., [20]) show earlier spring phenophase onsets in plants in recent years. Similar results were found in our study for *Betula pendula* (Tab. 7), an earlier phenophase onset for inflorescence emergence, beginning of flowering (10, 50 and 100%), and end of flowering in the decade 2001–2010. The differences between the first (1991–2000) and second decade (2001–2010) are from 2 to 10 days. The duration of interphase intervals is very variable (Tab. 16) and the reason can be the changes in the timing of phenophase onset. Our results show the superior role of temperature in the timing of phenological stages compared to precipitation (Tab. 19).

Pollen grains can be transported over medium or long distances. The pollen season start-date can be greatly influenced by dispersal types and this fact should therefore be taken into account when using airborne pollen data in phenological surveys. As recommended by Jato et al. [21], phenological studies should include major wind-pollinated tree species in order to improve the interpretation of airborne pollen data. Over recent years, Hirst volumetric pollen traps [15] have proved to be an accurate tool for crop forecasting [22,23]. Most equations combining phenology, airborne pollen counts and weather data provide accurate results.



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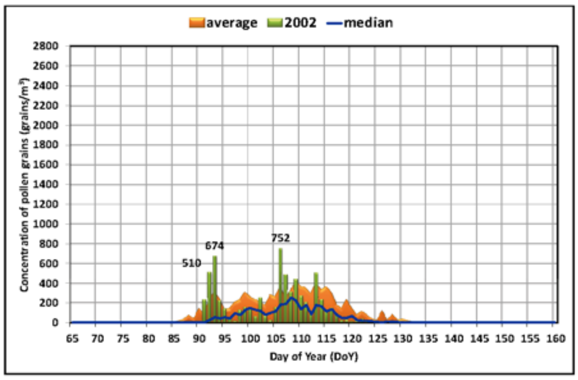

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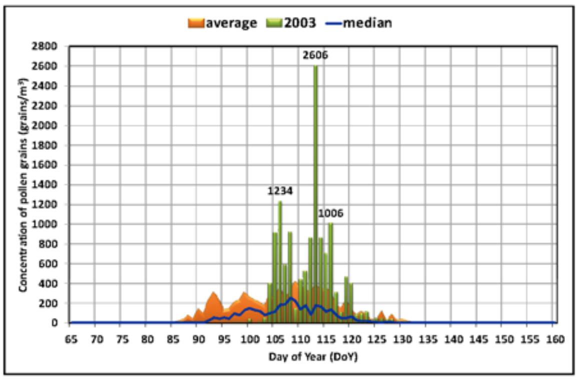

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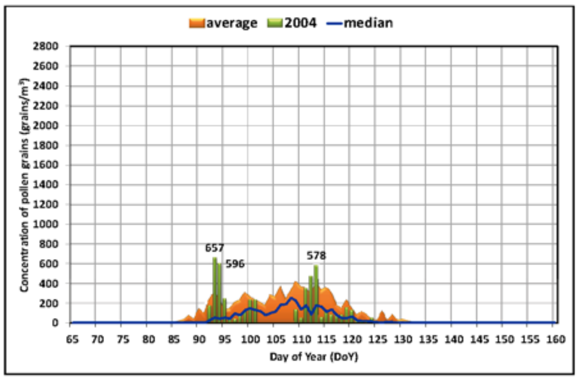

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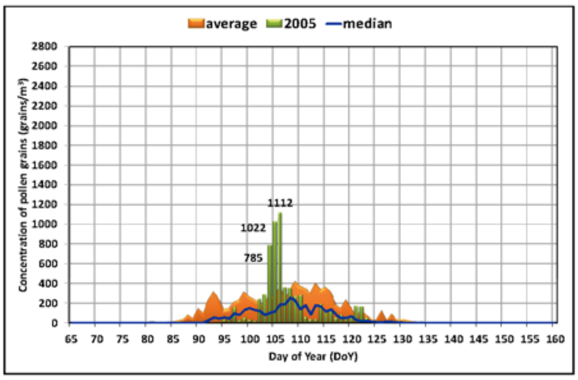

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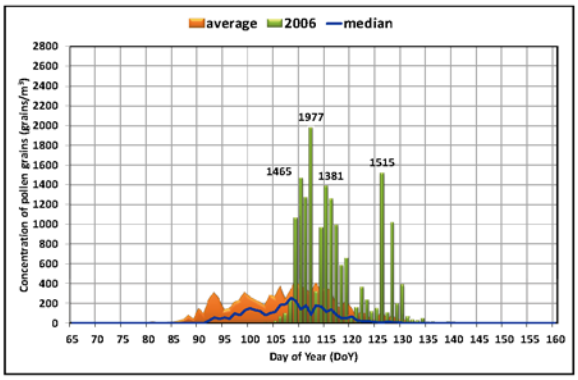

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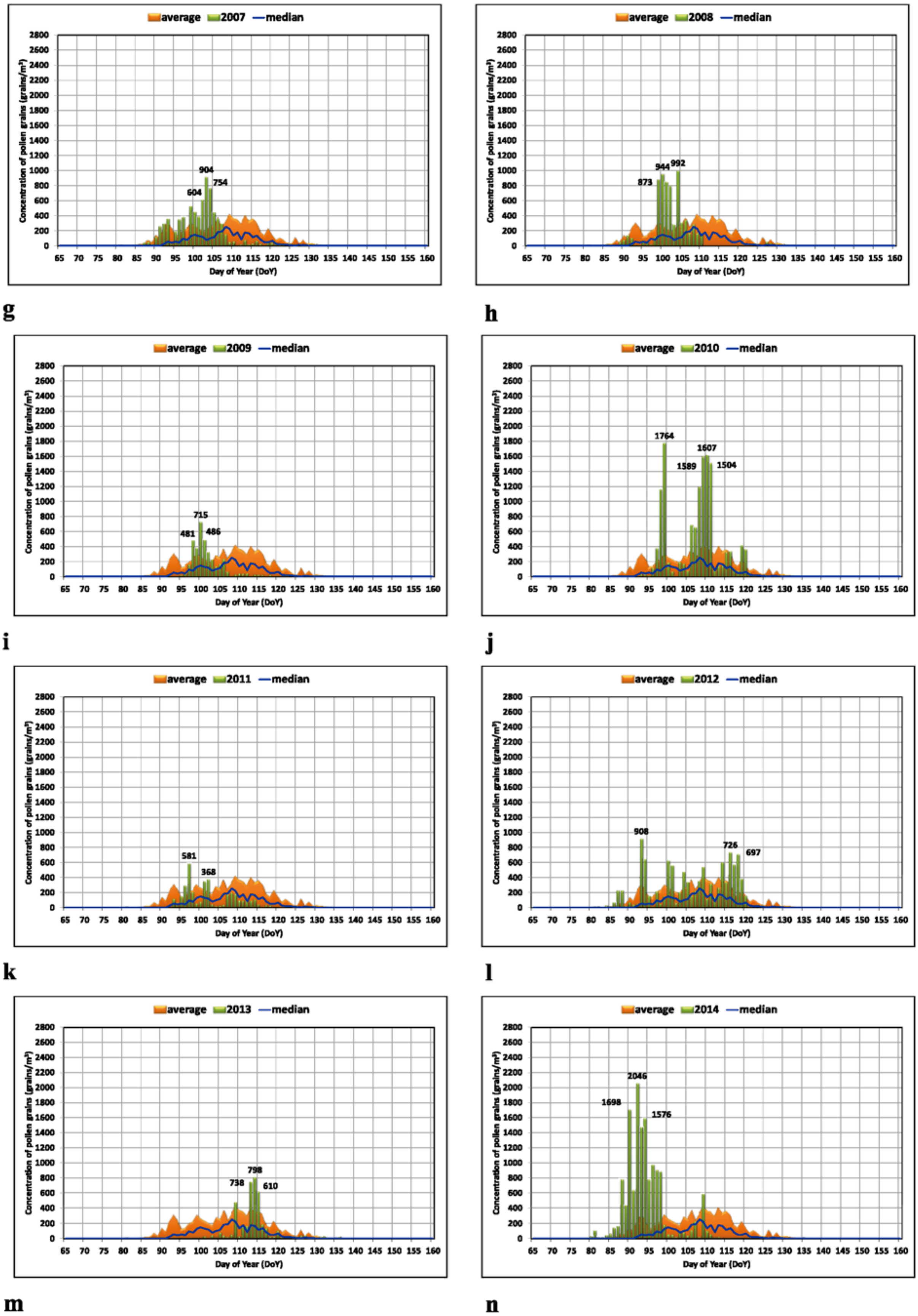

Fig. 16 Pollen grain counts in the years 2001 and 2002 (**a,b**), 2003 and 2004 (**c,d**), 2005 and 2006 (**e,f**), 2007 and 2008 (**g,h**), 2009 and 2010 (**i,j**), 2011 and 2012 (**k,l**), 2013 and 2014 (**m,n**).

Conclusions

Betula pendula (silver birch) is an important woody species included in the phenological observations program carried out across the Czech Republic by the Czech Hydrometeorological Institute.

The results of phenological observations during 1991–2015 (25 years) show considerable inter-annual differences in the beginning of particular phenophases and also in the duration of interphase intervals. The average timing of beginning of flowering 10% was 8th April (Lednice = lowland station) and 14th May (Modrava = mountain station); the average timing of beginning of flowering 50% was 12th April (Lednice station) and 20th May (Modrava station); the average timing of beginning of flowering 100% was 18th April (Lednice) and 22nd May (Modrava), and the average timing of end of flowering was 26th April and 28th May, respectively.

Later phenophase onsets were found in the years 1991, 1996 and 2010; earlier phenophase onsets were in the years 1993, 1997, 2007 and 2014. Both lowland and mountain stations report earlier phenophase onsets in the second decade, and the differences are higher at the Modrava station, i.e., in the mountains. For the inflorescence emergence phase, the difference was 29 days, the lowest sum of effective temperature (TS5) for this phase was 36.0°C (Lednice) and 9.3°C (Modrava), while the highest one was 170.1°C (Lednice) and 163.1°C (Modrava).

The beginning of flowering 10% phenophase (BF10%), differed 26 days between both stations, the lowest sum of effective temperature (TS5) for this phase was 48.3°C (Lednice) and 16.7°C (Modrava), while the highest one was 201.7°C and 173.7°C, respectively.

The beginning of flowering 50% phenophase (BF50%), differed 38 days between the analyzed stations, the lowest sum of effective temperature was 66.5°C (Lednice) and 21.0°C (Modrava), while the highest one was 243.1°C and 220.5°C , respectively.

The beginning of flowering 100% phenophase (BF100%), started at the Lednice station about 34 days earlier compared to Modrava, the lowest sum of effective temperature was 80.7°C (Lednice) and 49.1°C (Modrava), while the highest one was 292.8°C and 262.7°C, respectively.

The end of flowering phenophase (EF), started at the Modrava station about 28 days later, the lowest sum of effective temperature was 143.9°C (Lednice) and 59.5°C (Modrava), while the highest one was 371.9°C and 321.2°C, respectively.

The sums of effective temperatures above 5°C are very variable. It is considered whether temperature sums should be evaluated over another threshold with a more precise step (e.g., even with tenths of a degree) to find more accurate results for model prediction.

The period of occurrence of birch pollen in the air lasts 52 days on average in the Prague agglomeration and the highest concentration of pollen grains was 2606 pollen grains/m^3 (23rd April, 2003).

The most often found synoptic situations within interphase intervals were B, Bp, NEa, Sa and SWc2 (Tab. 20, Tab. 21) – this means both anticyclonic and cyclonic situations with northeast, south or southwest convection. It would be advisable to analyze synoptic situations together with other parameters (e.g., with the NAO index) to find better conclusions.

Potential pollen production is dependent on weather conditions during the previous winter; but weather conditions both prior to and during flowering also exert a marked influence on pollen dispersal and on the amount of pollen captured.

It is important to analyze all results of other CHMI phenological stations (across the whole Czech Republic), meteorological data (particularly air temperature, including extreme values), and results from Hirst volumetric pollen traps from all aerobiological stations for forecast model preparation.

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Authors' contributions

The following declarations about authors' contributions to the research have been made: idea of the study: LH, VK, LB, MM; phenological and aerobiological measurements: LH; statistical analysis: LH, VK, MM; writing of the manuscript: LH, VK, LB.

Competing interests

No competing interests have been declared.

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Zmiany kwitnienia brzozy na terenie Republiki Czeskiej w okresie 25 lat (1991–2015) w powiązaniu ze zmiennymi meteorologicznymi

Streszczenie

Praca przedstawia wyniki długookresowych obserwacji kwitnienia brzozy brodawkowatej (*Betula pendula*) prowadzonych w latach 1991–2015 w ramach fenologicznej sieci Czeskiego Instytutu Hydrometeorologicznego (CHMI – Český hydrometeorologický ústav). Dane zebrane w tym okresie wykorzystano do określenia terminów następujących fenologicznych faz generatywnego rozwoju brzozy związanych z jej pyleniem i występowaniem pyłku brzozy w powietrzu: formowanie kwiatostanów 10%, początek kwitnienia 10%, początek kwitnienia 50%, początek kwitnienia 100% i koniec kwitnienia. Stacje pomiarowe położone są na wysokości od 155 m n.p.m. (Doksany) do 1102 m n.p.m. (Modrava). Przeciętny termin początku kwitnienia 10% przypadał na 8 kwietnia (Lednice – niziny) i 14 maja (Modrava – góry); przeciętny termin początku kwitnienia 50% przypadał na 12 kwietnia (Lednice) i 20 maja (Modrava); przeciętny termin początku kwitnienia 100% przypadał na 18 kwietnia (Lednice) i 22 maja (stacja Modrava), a przeciętny termin końca kwitnienia odpowiednio na 26 kwietnia i 28 maja.

Sumy efektywnych temperatur powyżej 5°C (TS5) oraz dzienne sumy opadów zastosowano jako kryterium bioklimatologiczne w celu oceny zależności pomiędzy fazami fenologicznymi i zmiennymi meteorologicznymi. Średnie sumy TS5 oraz średnie dzienne sumy opadów były następujące: 61.0–80.8°C, 82.8–327.4 mm (formowanie kwiatostanów); 105.2–106.4°C, 85.9–365.2 mm (początek kwitnienia 10%); 124.8–130.8°C, 89.8–385.9 mm (początek kwitnienia 50%); 144.7–158.6°C, 95.2–390.7 mm (początek kwitnienia 100%); oraz 181.6–223.8°C, 104.7–427.4 mm (koniec kwitnienia). Uzyskano dane dotyczące występowania sytuacji synoptycznych w okresach międzyfazowych. Następujące układy synoptyczne obserwowane były najczęściej: B (front stacjonarny związany z zatoką niskiego ciśnienia nad Europą środkową), Bp (zatoka niskiego ciśnienia przemieszczająca się na wschód), NEa (północno-wschodni układ antycyklonalny), Sa (południowy układ antycyklonalny) oraz SWc2 (południowo-zachodni układ cyklonalny przemieszczający się w kierunku północno-wschodnim do wschodniego). Okres występowania pyłku brzozy w powietrzu trwa średnio 52 dni, a najwyższe stężenie zanotowano w dniu 23 kwietnia 2003 roku – 2606 ziaren pyłku/m^3.