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Increasing Risk of Spring Frost Occurrence during the Cherry Tree Flowering in Times of Climate Change

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Abstract: Climate change affects the agroecological conditions and persistence of cherry tree flowering. Detailed evaluation of minimum air temperature and occurrence of synoptic events occurrence during spring frosts within the cherry tree flowering in the Czech Republic (Central Europe) is missing. The main objective of this study was to evaluate the above-mentioned variables during the cherry tree flowering in different parts of the country from 1924 to 2012. Our question was how the frequency of frost days occurrence changed during the cherry tree flowering. A trend analysis was conducted with the Mann-Kendall test. The onset of the beginning of flowering and end of flowering shifted to an earlier date per the whole examined period (up to −13.9 and −8.1 days) and the period of flowering extended (up to 4.1 days). The shifts were more pronounced at higher elevations. During the period of the cherry tree flowering, the trend in change of the number of frost days was negative at the lowland station (−0.3 day) and positive at the highland station (+1.2 day). At all stations, "Ap3" synoptic event (anticyclone) occurrence during cherry tree flowering on days with the highest spring frost risk (T_{min} at 2 m < −1.1 °C) prevailed. The positive trend of frost-day occurrence and the negative trend of minimum air temperature in cherry tree flowering indicate that blossoms are more endangered at higher elevations.

Keywords: frost day; long-term time series; minimum air temperature; phenophase; synoptic event

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1. Introduction

The fact that many authors have found out a change in spring phenological onsets such as bud bursts, first leaves or beginning of flowering occur earlier and earlier with each decade (e.g., [1–4]) is well known nowadays. Although, minimum air temperatures were generally observed to increase more than maximum air temperatures in the Northern hemisphere (e.g., [5] or [6]) and plants are at greater risk during their phenological development. A temperature below 0 °C is one of the most dangerous weather conditions for plants in the vegetative season [7]. Destruction of flowers or young fruits by frost may cause significant economic loss for fruit and wine growers as it can dramatically reduce production and subsequent profit [8]. This may occur when a cold air mass prevails after a significant warm period in early spring that promotes premature vegetation development, which is also called a "false spring" [9].

Frost is an abiotic meteorological phenomenon that can have negative effects on plants and animals. The resistance against frost depends on many factors, e.g., on the plant type, the health condition of the plant itself, and on the current vegetation stage (phenological phase). Spring frost is a significant production hazard in nearly all temperate fruit-growing regions. Sweet cherries are among the first fruit varieties starting their development in spring and therefore highly susceptible to late frost [10]. Spring frost can be a limiting factor in fruit tree production [7]. Unless very severe frosts occur below the frost resistance limit of the plants, which will act for a longer period of time, the plants will survive the winter period without damage [11]. Damage by winter and spring frost is described by the critical temperature, respectively lethal temperature which causes the death of plant tissues. Unpredictable late spring frosts are a major risk to sweet cherries, and information on the critical temperatures of new cultivars is limited [12]. Timely phenological information is important in agriculture, fruit growing, forestry, medicine, tourism and wildfire management [13]. Phenology—the timing of seasonal activities of living organisms—is maybe the simplest method for tracking the response of species to environmental change [14]. The long-term phenological data series are a valuable biological source for climate change research. Notably, [15] stated that phenological shifts have been indicated as the biological footprint of the impact of climate change. Researchers [16] found out that long-term phenological data allow the reconstruction of temperature and its variability in the last centuries. Following the phenological series, an analysis of selected meteorological elements (e.g., the occurrence of a minimum air temperature below 0 °C at the time of fruit trees flowering) or the change in frequency of synoptic events occurrence in a period of flowering can be performed. The fact of earlier spring flowering is closely associated with the growing risk of spring frosts at the time of fruit trees flowering. Many authors have examined the increase in the risk exposure of fruit trees to spring frosts in their country, e.g., [17] evaluated this task in Switzerland. High losses in fruit and wine growing have been and are being recorded, especially in the last decades. The important parameter is how long the frost acts on the tree, e.g., during the flowering of cherries, the dangerous frost is from −1.1 to −2.2 °C lasting longer than 60 min [18]. Unfortunately, due to the length of the time series (since 1924), there were no available hourly values of the minimum air temperature, so the daily minimum air temperature as a proxy variable was used.

The research question of this study was how the occurrence of late spring frosts changed and how the vulnerability of the cherry tree flowering changed in different temperature zones of the Czech Republic. The Czech Republic is a world producer and exporter of cherries.

The main particular activities of this study were as follows:

(1) to make the temporal evaluation of the beginning of flowering, end of flowering and duration of the cherry tree (*Cerasus avium*) flowering at long-term phenological stations situated in the different climatic conditions of the Czech Republic in the period of 1924–2012 and the periods of 1924–1967 and 1968–2012,
(2) to analyze the minimum air temperature (including the number of frost days) during the period of the cherry tree flowering from 1961 to 2012,
(3) to process the frequency of synoptic event occurrence during the period of the cherry tree flowering in the period of 1946–2012.

Our hypotheses were (1) the shift of the phenological phase to an earlier date causes a greater vulnerability of the cherry tree, and (2) the number of frost days during the cherry tree flowering will decrease under climate warming.

2. Material and Methods

The Czech Hydrometeorological Institute (CHMI) manages the phenological network of different plants (fruit trees, wild plants and field crops). The phenological observations have a long tradition in the Czech Republic and the CHMI archive contains the phenological reports of fruit trees from 1924 to 2012. These reports include the monitoring of many trees, e.g., cherry trees (*Cerasus avium*). In this study, the long-time series of the cherry tree from four phenological stations situated in various climatic conditions of the Czech Republic (Figure 1) were used. At all stations, the "Rychlice německá"variety (cultural variety) was observed. The phenological stages such as the beginning of flowering and end of flowering (Figure 2) were selected for this research. The regular phenological observations were performed according to the methodology ([19–21]). At least 5 individuals were monitored at each monitoring site. Phenological dates are stated on the day of year (DoY). The corresponding meteorological station was assigned to each phenological station (Table 1) in order to gain the daily minimum air temperature (minimum air temperature is the most threatening meteorological variable for cherry blossoms) at the time of the flowering and to describe the climatological conditions of the phenological stations (Table 2).

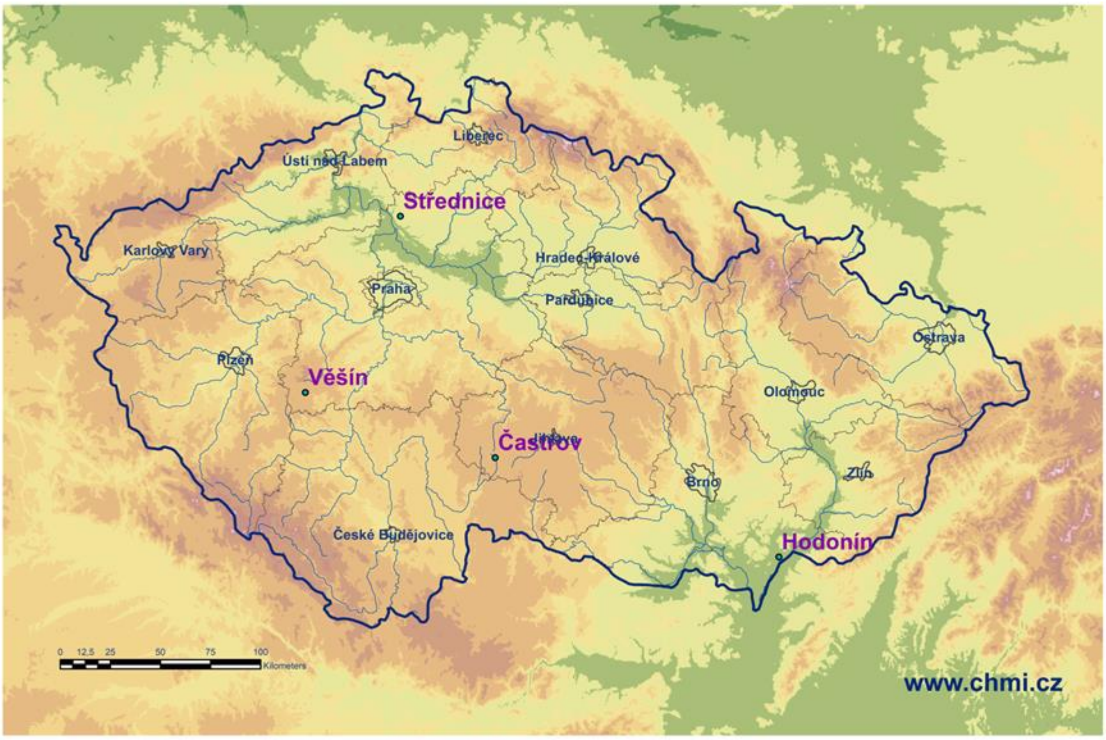

Figure 1. Location of the selected phenological stations (highlighted in violet).

Figure 2. Beginning of flowering and end of flowering of the cherry tree (*Cerasus avium*).

The long-term (1924–2012) phenological data were gained from the CHMI phenological database PHENODATA. Meteorological data (1961–2012) were exported from the CHMI climatological database CLIDATA. The quality control and correction of inhomogeneities have been completed on a daily basis for all key meteorological variables over the territory of the Czech Republic. AnClim software was used [22]. The types of weather circulation conditions (synoptic events) were obtained from the CHMI website [23] in period from 1946 to 2012.

Table 1. Characteristics of the phenological (P) and climatological (C) stations including Quitt's classification [24].

Station	Longitude	Latitude	Altitude (m a.s.l.)	Station	Longitude	Latitude	Altitude (m a.s.l.)	Quitt's Classification
Hodonín (P)	17°48′	48°52′	174	Hodonín (C)	17°48′	48°51′	172	W4
Střednice (P)	14°31′	50°24′	290	Doksany (C)	14°10′	50°27′	158	W2
Věšín (P)	13°50′	49°37′	565	Příbram (C)	14°01′	49°41′	555	MW4
Častrov (P)	15°18′	49°31′	620	Nový Rychnov (C)	15°16′	49°24′	619	MW4

Note: W2, W4—warm regions; MW4—medium warm region.

Table 2. Climatological characteristics of the phenological stations.

Station	tyear (°C)	abs tmax (°C)	tmax July (°C)	tmin January (°C)	abs tmin (°C)	tmin > 0.0 °C (Days)	ryear (mm)	abs rmax (mm)	r > 0.1 mm (Days)
1961–1986									
Hodonín	9.1	35.6	25.0	−5.4	−28.6	261	533.9	79.9	128
Střednice	8.6	36.7	24.2	−5.0	−26.3	263	451.3	78.0	154
Věšín	7.0	37.3	22.3	−5.3	−23.5	243	515.6	95.7	161
Častrov	6.6	36.5	21.7	−6.6	−27.2	231	599.1	54.3	196
1987–2012									
Hodonín	9.8	37.6	26.5	−4.2	−25.5	263	535.4	58.4	123
Střednice	9.5	38.2	26.0	−3.4	−25.9	270	471.7	63.0	162
Věšín	7.8	36.4	23.4	−4.0	−24.4	254	524.5	73.4	166
Častrov	7.5	35.3	23.1	−5.2	−23.9	241	673.7	74.0	197

Notes: tyear = average year air temperature (°C), abs tmax = absolute maximum of air temperature, tmax July = average monthly maximum of air temperature of the warmest month, tmin January = average monthly minimum of air temperature of the coldest month, abs tmin = absolute minimum of air temperature, tmin > 0.0 °C = average count of days with air temperature minimum >0.0 °C, ryear = average cumulated year precipitation.

The period of the flowering was determined each year as well as the number of days below −1.1 °C was assessed (minimum air temperature below −1.1 °C is very unfavorable for cherry tree flowering [18].

The trend analysis was conducted using the Mann-Kendall (M-K) test. The M-K test is non-parametric and does not require the data to be distributed normally. The M-K test is typically used in the natural sciences.

3. Results

The onset and duration of the cherry tree flowering differed considerably between the years (Figure 3) and descriptive statistics for the beginning and end of cherry tree flowering in the periods of 1924–2012, 1924–1967 and 1968–2012 are shown in Table 3.

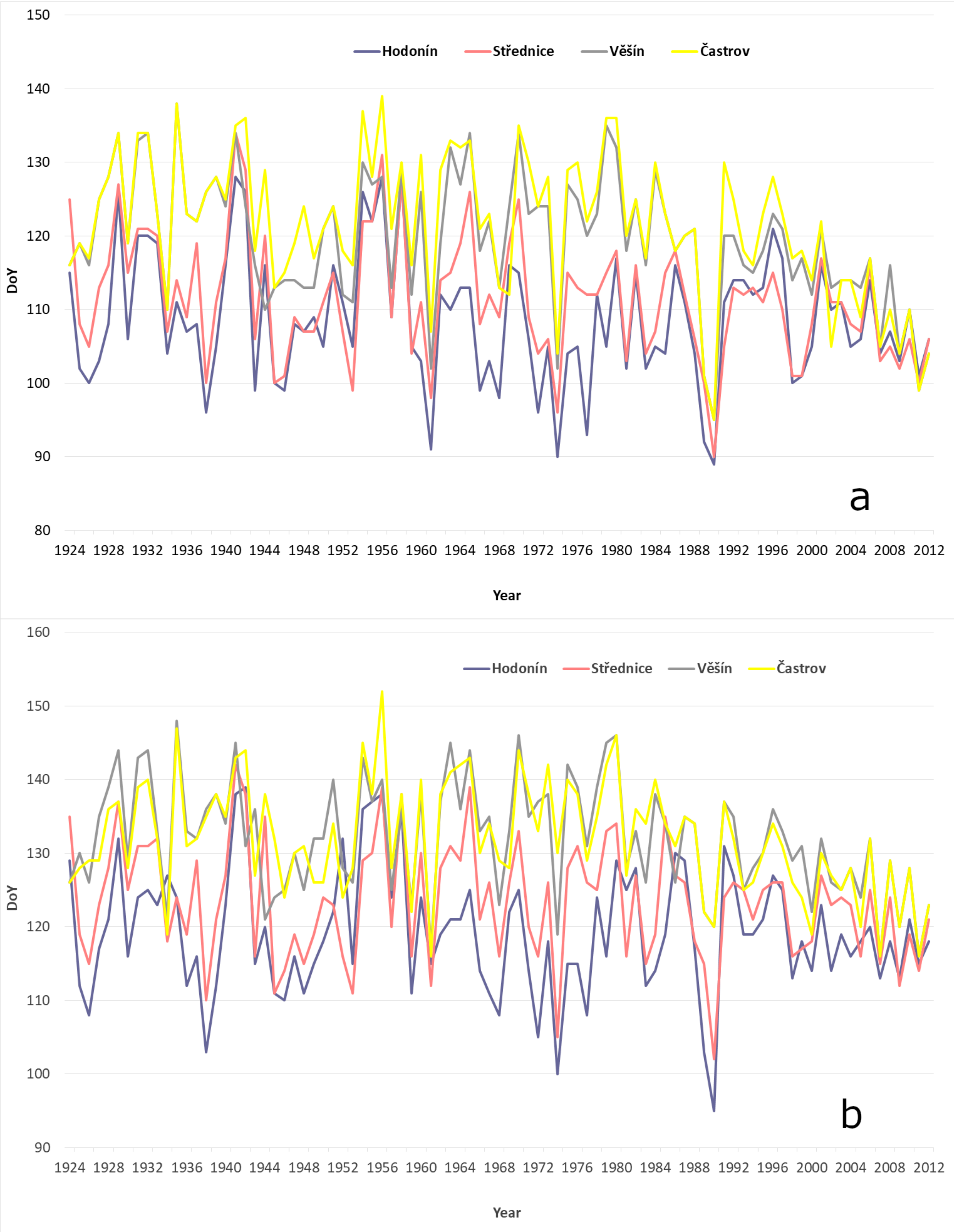

Figure 3. Beginning of flowering (**a**) and end of flowering (**b**) of *Cerasus avium* at Hodonín, Střednice, Věšín and Častrov stations in the period of 1924–2012 (in DoY).

Table 3. Descriptive statistics for the beginning of flowering and end of flowering of *Cerasus avium* in the periods 1924–2012; 1924–1967 and 1968–2012 (in DoY).

Station	Period	Average	Minimum	Maximum	Standard Deviation
		Beginning of flowering			
Hodonín	1924–2012	109	89	128	8.7
Střednice	1924–2012	111	90	134	8.3
Věšín	1924–2012	119	95	138	8.9
Častrov	1924–2012	121	95	139	9.6
Hodonín	1924–1967	110	91	128	9.4
Střednice	1924–1967	113	98	134	9.1
Věšín	1924–1967	122	102	138	8.3
Častrov	1924–1967	125	107	139	7.9
Hodonín	1968–2012	107	89	121	7.6
Střednice	1968–2012	109	90	125	6.7
Věšín	1968–2012	117	95	135	8.9
Častrov	1968–2012	118	95	134	10.2
		End of flowering			
Hodonín	1924–2012	119	95	139	8.7
Střednice	1924–2012	123	102	142	8.0
Věšín	1924–2012	132	116	148	7.7
Častrov	1924–2012	132	116	152	7.6
Hodonín	1924–1967	121	103	139	9.1
Střednice	1924–1967	125	110	142	8.7
Věšín	1924–1967	134	117	148	7.6
Častrov	1924–1967	130	116	146	7.3
Hodonín	1968–2012	118	95	131	7.9
Střednice	1968–2012	122	102	135	7.0
Věšín	1968–2012	131	116	146	7.6
Častrov	1968–2012	130	116	146	7.3

The mean date of the beginning of flowering for 89 year period is between 19th April (Hodonín) and 1st May (Častrov), and the mean date of the end of flowering is between 29th April (Hodonín) and 12th May (Častrov). How the mean date and other statistical characteristics of selected phenological phases changed in other periods are listed in this table. At all stations, the earliest mean date of the beginning and end of flowering was found in the period of 1968–2012. The earliest date of the beginning of flowering oscillated between 30th March (Hodonín station in 1990) and 5th April (Častrov station in 1990), and the latest date of the beginning of flowering was within the range of 8th and 19th May (at Hodonín station it was in 1958 and at Častrov station it was in 1956). The earliest date of the end of flowering is between the 5th and 26th of April (at Hodonín station it was in 1990 and at Častrov station it was in 1961) and the latest date was between the 19th of May and 1st June (at Hodonín station it was in 1942 and at Častrov station it was in 1956).

The length of the flowering periods was approximately 10 days on average. The longest period was detected in the period of 1961–2012 (26 days) and the shortest duration was in the period of 1924–1967 (Table 4). Table 5 shows the results of the M-K test. In total, trends in the phenophase onsets were negative (it means earlier onset) in the period of

1924–2012, but the duration of flowering was prolonged (significantly higher at Častrov station which is located in the highlands). Trend analysis of the number of frost days occurrence (Table 6), during the period of flowering, was negative at Hodonín station (lowland station) and positive at Častrov station (highland station).

Table 4. Descriptive statistics for the period of flowering of *Cerasus avium* in the periods 1924–2012; 1924–1967 and 1968–2012 (in days).

Station	Period	Average	Minimum	Maximum	Standard Deviation
Period of flowering					
Hodonín	1924–2012	11	4	24	4.9
Střednice	1924–2012	12	7	20	3.1
Věšín	1924–2012	13	7	25	3.3
Častrov	1924–2012	10	3	26	4.5
Hodonín	1924–1967	10	4	24	5.1
Střednice	1924–1967	11	7	19	2.4
Věšín	1924–1967	12	7	20	2.9
Častrov	1924–1967	9	3	19	2.6
Hodonín	1968–2012	11	4	23	3.9
Střednice	1968–2012	13	7	20	3.4
Věšín	1968–2012	13	8	25	3.5
Častrov	1968–2012	12	5	26	5.3

Table 5. Results of the M-K test of the beginning of flowering, end of flowering and period of the cherry tree flowering in the period of 1924–2012.

Station	Variable	Slope Change/Year	Days/Period
Hodonín	Beginning of flowering	−0.036	−3.2
Střednice	Beginning of flowering	−0.105 **	−9.3
Věšín	Beginning of flowering	−0.143 ***	−12.7
Častrov	Beginning of flowering	−0.158 ***	−13.9
Hodonín	End of flowering	−0.029	−2.6
Střednice	End of flowering	−0.068 *	−6.1
Věšín	End of flowering	−0.095 **	−8.5
Častrov	End of flowering	−0.092 **	−8.1
Hodonín	Period of flowering	0.016	+1.4
Střednice	Period of flowering	0.038 **	+3.4
Věšín	Period of flowering	0.04 ***	+3.6
Častrov	Period of flowering	0.05 ***	+4.1

Note: * significant trend at $\alpha = 0.05$. ** significant trend at $\alpha = 0.01$. *** significant trend at $\alpha = 0.001$.

Table 6. Results of M-K test of number of frost days in period of the cherry tree flowering (1961–2012).

Station	Slope Change/Year	Days/Period
Hodonín	−0.006	−0.3
Střednice	−0.005	−0.26
Věšín	0.022 **	+1.1
Častrov	0.023 **	+1.2

Note: ** significant trend at $\alpha = 0.01$.

The dates of the beginning of flowering and end of flowering over the period of 1961–2012 were compared with the minimum air temperature (T_{min}). At Hodonín station, it was found that the lowest value of T_{min} occurred in the year of 1968 (−4.9 °C), at Střednice station, it was found in the year of 1988 (−5.7 °C), at Věšín station, it was found in the year of 1990 (−4.2 °C) and at Častrov station, it was found in the year of 2005 (−4.7 °C). The average value of the lowest minimum air temperature during the period of the cherry tree flowering was positive at all stations: 0.6 °C (Hodonín station), 0.2 °C (Střednice station), 1.2 °C (Věšín station) and 0.7 °C (Častrov station). The results of the Mann-Kendall test of the minimum air temperature during cherry tree flowering are positive at Hodonín and Střednice stations (lowland stations) and negative at Věšín and Častrov stations (highland stations)—Table 7. Figure 4 illustrates the number of days with $T_{min} < -1.1$ °C during the cherry tree flowering. The average number of days with $T_{min} < -1.1$ °C reached the same value at both stations (0.6 days), and the maximum value of these days was at the Častrov station 6 days (in 1990) and at the Hodonín station 4 days (in 1981 and 1988).

Table 7. Results of the M-K test of the minimum air temperature in the period of the cherry tree flowering in the period of 1961–2012.

Station	Slope Change/Year	°C/Period
Hodonín	0.004	0.21
Střednice	0.004	0.21
Věšín	−0.0125 **	−0.65
Častrov	−0.0125 **	−0.65

Note: ** significant trend at $\alpha = 0.01$.

The frequency of the synoptic events [23] occurrence during the cherry tree flowering in the period of 1946–2012 is plotted in Figure 5, the highest frequency was found by "B" synoptic event [23] occurring during the days with $T_{min} < -1.1$ °C are mentioned in Figure 6 (occurrence (Figure 7b)). At all stations, "Ap3" synoptic events [23] during the highest spring frost risk prevailed (Figure 7a). In total, the period with the highest frequency of spring frost occurrence predominated anticyclonal synoptic events (Table 8).

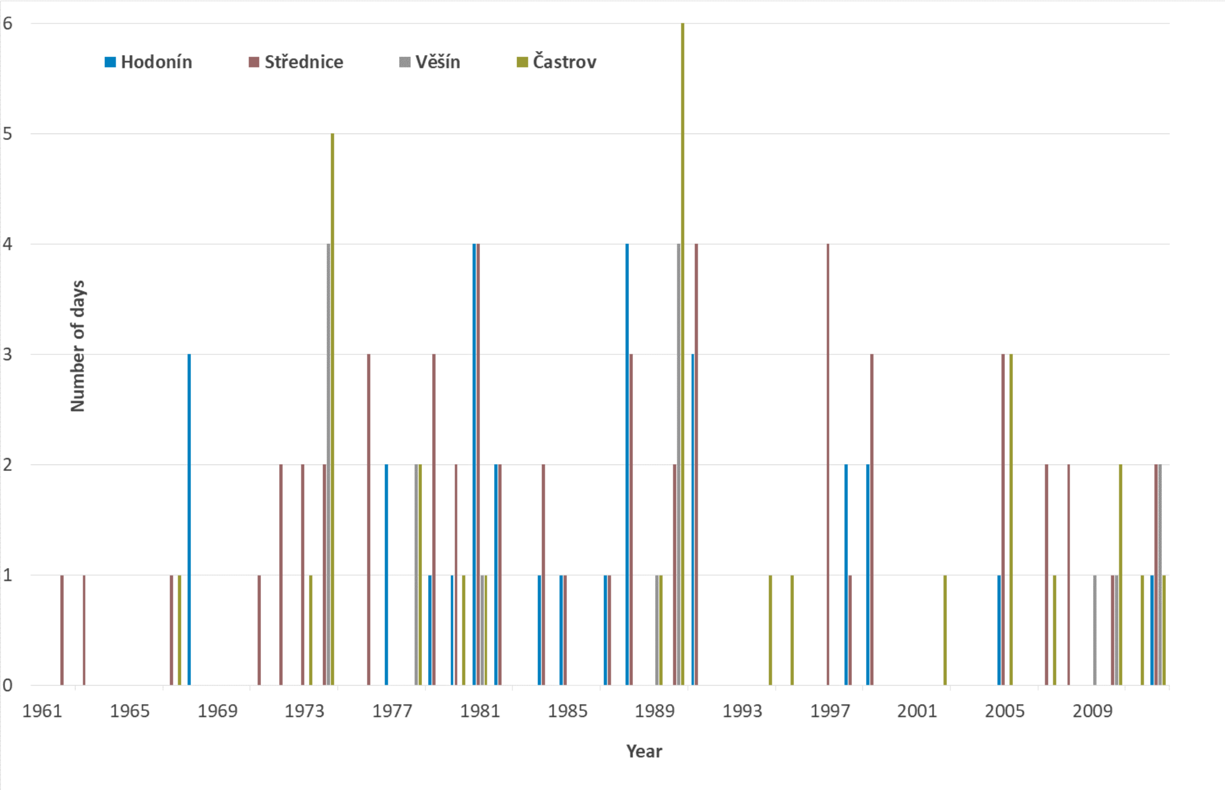

Figure 4. Number of days with $T_{min} < -1.1$ °C during the period of the cherry tree flowering in the period of 1961–2012.

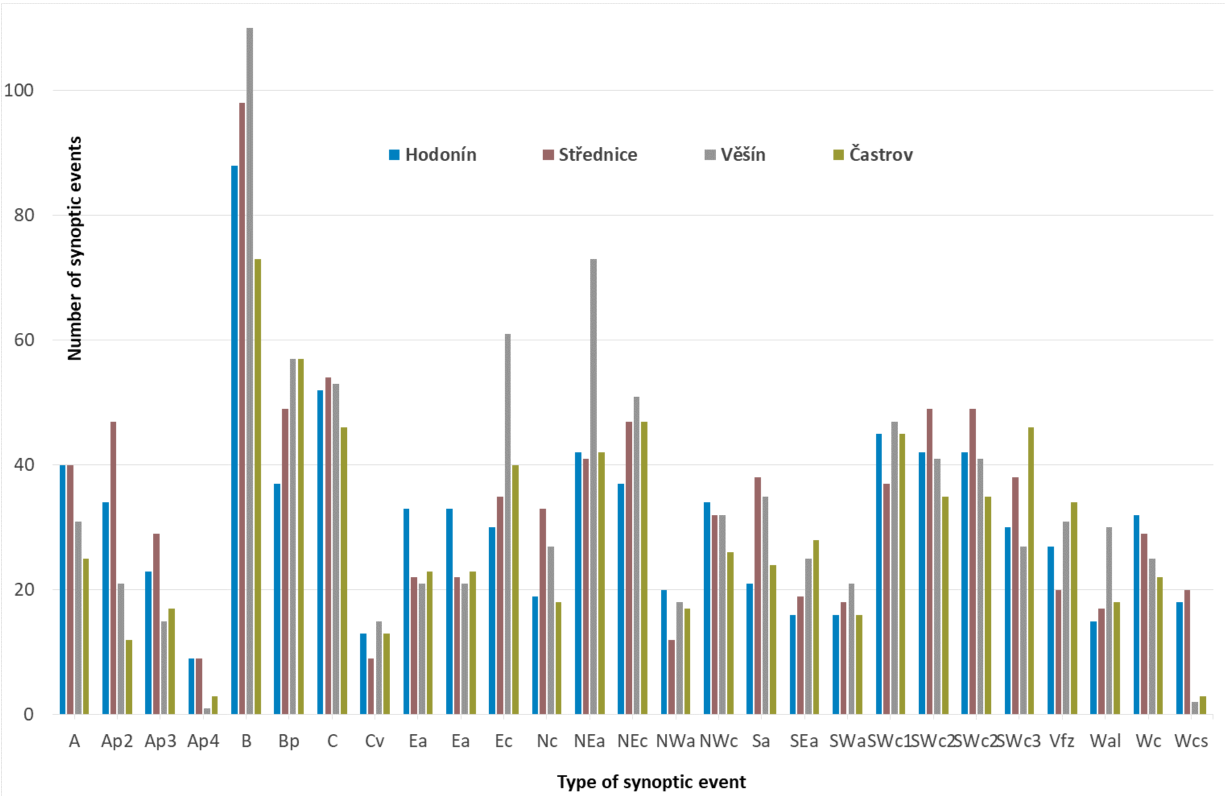

Figure 5. Frequency of synoptic events occurrence during the period of the cherry tree flowering (period of 1946–2012).

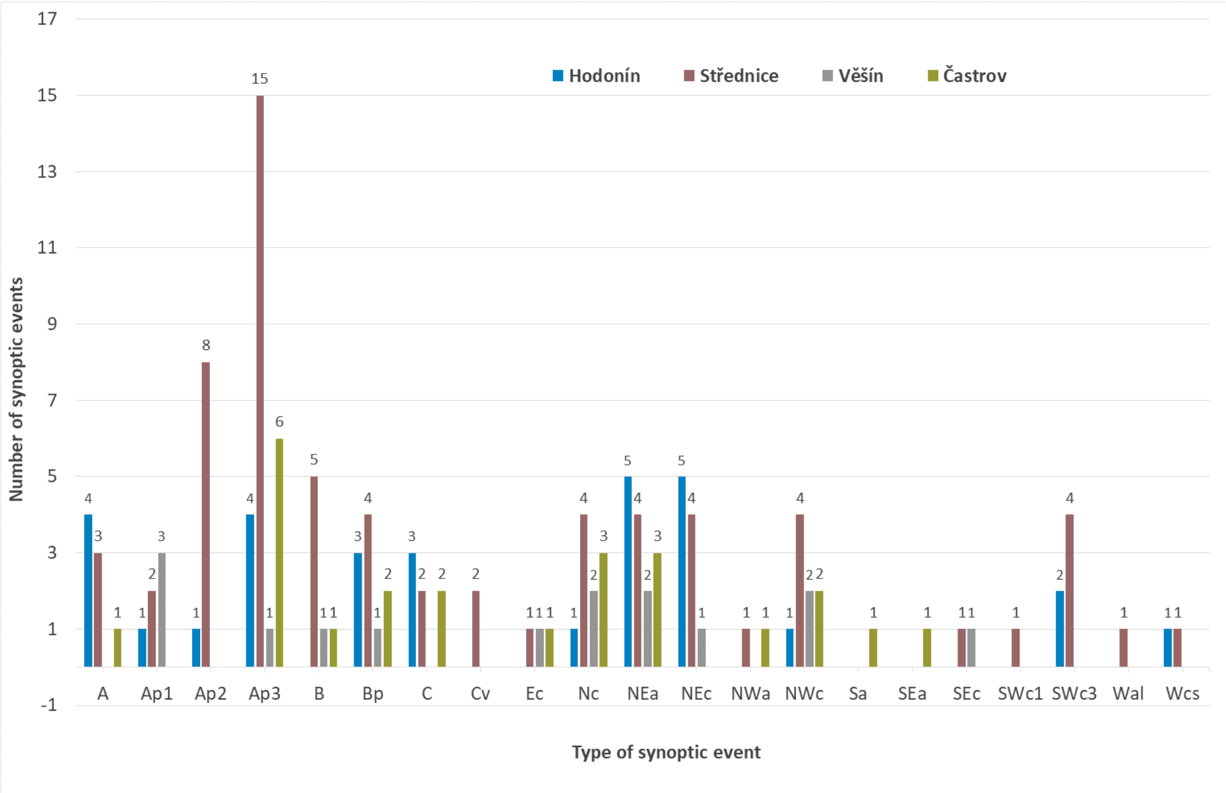

Figure 6. Frequency of synoptic events occurrence in the period of the cherry tree flowering during days with $T_{min} < -1.1$ °C (period of 1961–2012).

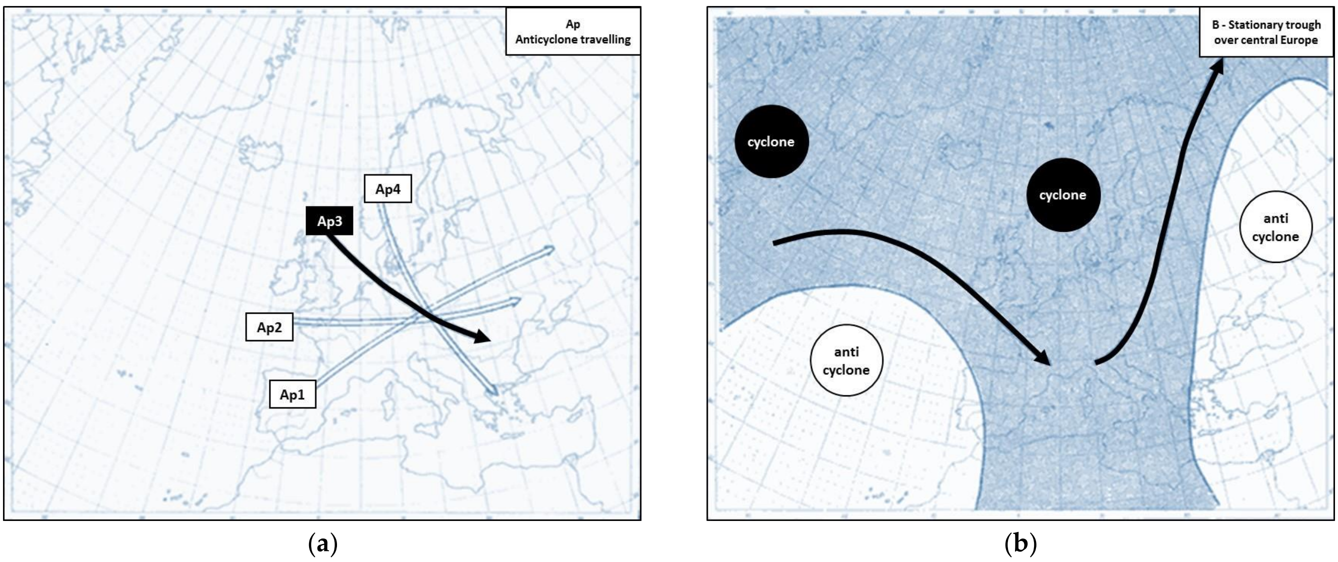

Figure 7. "Ap3" (**a**) and "B" (**b**) synoptic events.

Table 8. Frequency of synoptic event occurrence in the period of the cherry tree flowering during days with $T_{min} < -1.1$ °C (period of 1961–2012).

Type/Station	Hodonín	Střednice	Věšín	Častrov
Anticyclonal synoptic event	15	34	6	13
Cyclonal synoptic event	12	23	7	8
B	0	5	1	1
Wcs	1	1	0	0
Bp	3	4	1	2

4. Discussion

The main goal of this study was to make the temporal assessment of the beginning of flowering, end of flowering and duration of flowering of the cherry tree (period of 1924–2012) at the phenological stations situated in various climatic conditions of the Czech Republic, and in addition to evaluate the minimum air temperature and synoptic events occurrence during the period of the cherry tree flowering.

The sensitivity of different plant species to low temperatures (below zero) is very variable. It can be different for individual cultivars, and it also varies during the life of the plants. Although the plants in temperate zones are more adapted to low temperatures, sudden temperature drops are harmful to them. Notably, [8] stated that in temperate climates, significant damage to deciduous fruit trees is raised in buds and developing fruits after dormancy, and economic losses due to frosts during the flowering period are usually more important than those due to low winter temperatures. Notably, [25] found out that flowering is affected by climate change due to the changes in chill accumulation and the number and timing of days with frosts. Our study showed that the number of increasing frost days at the highlands during the period of the cherry tree flowering may adversely affect the final cherry tree production. It was confirmed by the results of [26] that even though it is assumed that despite warming trends in all seasons in Central Europe, the risk of cold spells in winter and frost days in spring will still remain. Notably, [12] examined the response of cherry flower parts to freezing stress and found out that some cherry cultivars (e.g., “Stela”, “Vista” and “Early Burlat”) were the most freezing-tolerant during bud development stages. Notably, [27] discovered that the temperatures causing 50% frost damage for cherry tree flower buds were −2.08 to −3.6 °C at the side green stage, −1.49 to −3.22 °C at the green tip stage, −1.18 to −1.98 °C at the open cluster stage, −7.92 to −9.96 °C at the first white stage, and −6.29 to −9.36 °C at the full bloom stage. In this research was the lowest value of minimum air temperature during the period of cherry tree flowering −4.9 °C (Hodonín lowland station) and −4.7 °C (Častrov highland station).

Our phenological findings (trend of earlier phenophase onset) confirmed that phenology is a great tool for detecting and measuring the impact of climate on vegetation. With respect to analyzing the time series of the phenological phases, it can be stated that the strength of the trends depends to a great extent on the period considered [28]. The nearly 90-year series confirms this statement (shift of the phenophase onset up to −13.9 days by the beginning of flowering and up to −8.1 days by the end of flowering). The number of frost days during the flowering was negative at lowland stations, and conversely positive at highland stations. In addition, with the earlier onset of spring, the number of frosty days is increasing not only in the Czech Republic [29] but also in Europe [30]. These findings locally confirmed global warming and the dangerous influence of early spring frost risk on the cherry tree flowering in highlands (earlier onset of the beginning of flowering is at great risk of a sudden influx of cold air during spring). As [31] concluded in their study, knowledge and awareness of flower bud phenological stages and fruit growth development are important requirements for many aspects of crop management. Moreover, spring frost losses could increase in the future and it is reasonable to assume that these developments will be highly localized, depending on whether the climate is continental or maritime, and whether a location is at altitude or in a valley. Notably, [7] revealed in their study the importance of reliable phenological models which not only work for current but also for changed climate conditions and at different sites. Notably, [17] suggested in their results that frost risk needs to be considered carefully when promoting the introduction of new varieties of fruit trees in warmer and drier climates or when considering new plantations at higher elevations. Freeze damage is one of the main limiting factors to horticultural crop production [8]. Many authors, e.g., [17] suggested that frost risk needs to be considered carefully when promoting the introduction of new fruit tree varieties adapted to a warmer and drier climate. Similar findings were found [12] in their research about the sensitivity of cherry trees to sub-zero temperatures.

In total, it was found that in the period of the highest frequency of spring frost occurrence, anticyclone types of synoptic events prevailed. Notably, [2] have shown that the last spring freeze of either 2.2 °C or lower temperatures has also become more variable and since the earlier onset of spring, plants are now more prone to frost damage due to synoptic events. Moreover, [13] discovered in their research that the spring flowering index correlates with the incidence of El Niño events and with Pacific sea-surface temperatures.

5. Conclusions

This paper examined the temporal assessment of the beginning of flowering, end of flowering, and period of flowering of the cherry tree in different climatic conditions in the Czech Republic. The research was conducted in the period of 1924–2012. The phenological data were compared with the minimum air temperature and frequency of synoptic events occurrence. The results showed that the trend in phenophase onsets and length of the period of flowering is different. The onset of the beginning and end of flowering occurred earlier. Conversely, the period of flowering extended, and at the highland station, the shift was more pronounced. The highest number of days with minimum air temperature below −1.1 °C during the period of flowering oscillated from 4 days to 6 days and the trend in the change of the number of frost days was negative at lowland stations and positive at highland stations. At all stations, "Ap3" synoptic event (anticyclone) occurrence during cherry tree flowering in the period with the highest spring frost risk prevailed. The results of the M-K test of the minimum air temperature during cherry tree flowering are positive at lowland stations and negative at highland stations. Protecting the orchards from adverse spring frosts is a very important step in growing fruit trees to ensure a bountiful harvest. The use of artificially produced fog is only one of the variants of how to protect fruit trees. Furthermore, there is indirect protection in the form of the right location of the land and the selection of the appropriate cultivated species.

This research found that cherry tree flowering is more endangered in the highlands than in the lowlands of the Czech Republic. The regional studies with projections based on the climate models including changes in the circulation conditions (synoptic events occurrence) would be essential to supplement risk management in fruit growing and can help growers to estimate possible frost damages on cherry trees.

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