RESEARCH

Past and present risk of spring frosts for fruit trees in the Czech Republic

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Abstract
Recent climate warming is reflected in the advanced onset of spring phenological phases of fruit trees and in so-called false springs. This then manifests as an increased risk of trees being damaged by late frosts in the sensitive growing stage. Based on the homogenised temperature series of 155 climatological stations divided into two altitudinal groups (below 300 m a.s.l. and 301–600 m a.s.l.), a climatological analysis of selected variables in relation to atmospheric circulation over the territory of the Czech Republic during the period 1961–2021 was performed. The number of frost days and the dates of their latest onset exhibited negative linear trends; however, only 16% and 20% were statistically significant. The onset of false spring (at least ten consecutive days with daily maximum ≥ 10 °C) was also characterised by decreasing trends, which significantly deepened after 1980. Spring frost days were particularly attributed to higher frequencies of anticyclonic circulation types such as the central anticyclone and circulation types with northeastern, eastern and southeastern airflow. False spring onset was particularly connected with the central anticyclone and circulation types with western and southwestern airflow. The increasing trends of frost risk days (days between the beginning of the false spring and the date of the latest frost with daily minimum < -1.5 °C) were statistically nonsignificant. Local series of fruit trees from southeastern Moravia proved to have significantly earlier onset of the first blossom and full blossoming phenophases. Although the damage by late frosts has been identified as an important factor contributing to low yields of fruit trees during the period 1996–2021 in the Czech Republic, other factors (e.g. other weather phenomena, diseases, pests, site, taking preventive measures against frost) must also be taken into account.

1 Introduction

The recent climate warming starting from the late 1970s has significantly changed the values and variability of temperature characteristics from local/regional to continental to global scales (e.g. Wang et al. 2018; Twardosz et al. 2021;

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Brázdil et al. 2022). Increases in minimum daily temperatures (TMIN) significantly influence the seasonal occurrence and severity of frosts, which are generally documented by the decrease in the number of frost days (TMIN < 0.0 °C), by the earlier onset of spring frosts, by the later onset of autumn frosts and subsequently by the prolongation of free-frost periods, as recorded, for example, for the USA in 1948–1999 (Easterling 2002), Poland in 1961–2020 (Graczyk and Szwed 2020) and 1971–2020 (Koźmiński et al. 2023), central Europe in 1951–2010 (Wypych et al. 2017) or central and southeastern Europe in 1950–2019 (Chervenkov and Slavov 2022). Regarding long-term change, Štěpánková (2005) found a statistically significant decreasing linear trend in the number of spring frost days by −0.28 days/10 years for the Prague-Klementinum station (Czech Republic) for the period 1775–2003. These changes have many important consequences and impacts in different sectors, such as agriculture, horticulture, forestry and the power industry, as reflected in high levels of risk and

damage and contributing to tremendous economic losses and dramatic ecological effects (e.g. Lamichhane 2021).

Of particular concern are the late spring frosts defined here as below-freezing temperatures occurring in the late spring, after a substantial warming in preceding days. Rising temperatures in the late winter and early spring may trigger a so-called "false spring" (Peterson and Abatzoglou 2014), during which the early onset of tree phenology can be followed by cold spells with frosts (Chamberlain et al. 2019; Ma et al. 2019), particularly dangerous during blooming when frosts damage buds, flowers and developing fruits after dormancy (Rodrigo 2000). The effects of frost on vulnerable plant organs markedly impact the growth, health, competitive ability and distribution limits of plants (Lamichhane 2021). Some outstanding false springs, such as those in the USA in 2007 (Gu et al. 2008; Demirsoy et al. 2022), 2010 (Hufkens et al. 2012) or 2012 (Labe et al. 2017), have been used as an example of potential future impacts of late spring frosts. The most damaging late spring frosts in Europe were recorded in 2017 (Faust and Herbold 2018; Vitasse and Rebetez 2018). Hulsmann et al. (2023) pointed out the increasing risk of a false spring for cherry trees in Europe during the period 1981–2021, particularly in southern Scandinavia and the Baltic states.

Liu et al. (2018), investigating the number of frost days during the growing season between 1982 and 2012, noted a significant increase across approximately 43% of the Northern Hemisphere (for latitudes above 30°N), especially for Europe and during spring. Regions with larger increases in growing season length also experienced greater increases in frost days. Zohner et al. (2020) analysed late-spring frosts, leaf-out phenology and leaf-freezing resistance data recorded between 1959 and 2017 from up to 1500 species cultivated in common gardens in temperate and boreal regions of the Northern Hemisphere. They found that 35% of European and 26% of Asian forests are increasingly threatened by frost damage compared to only 10% in North America. Ma et al. (2019) demonstrated for 27 tree species in Europe that temporal changes in the risk of spring frost damage depend on the species and geographical locations when the maritime and coastal areas were more exposed to late spring frosts than the continental areas.

Many papers have investigated the effects of frost on individual fruit trees. For example, Eccel et al. (2009) reported a lower risk of exposure to spring frost for apple production in the Trentino region (Italy) at present compared to the past. Lakatos et al. (2016) showed that in fruit-growing regions of western and eastern Hungary, the damage severity of spring frosts was largely dependent on the temperature of the preceding days, while the earlier bloom was followed by heavier damage. Vitasse et al. (2018) found an increasing risk of frosts for the flowering and leaf-out timing of apple and cherry trees with subsequent potential damage

in locations above 800 m a.s.l. in Switzerland from 1975 to 2016, while risk in locations at lower elevations remained unchanged. Pfleiderer et al. (2019) pointed out that for Germany, in a future 2 °C warmer world, the increased risk of frost damage for apple trees will be up to 10% higher than that of the present day. Cebulj et al. (2022) investigated how the occurrence of frost rings related to spring frosts affects sugar, organic acid, and phenol content in the flesh and phenol content in the peel of apple fruit. The effects of spring frost have also been analysed for other fruit trees in addition to apple, such as cherry (Matzneller et al. 2016; Demirsoy et al. 2022) and peach (Çetinbaş et al. 2021). Drepper et al. (2022) performed a systematic review of strategies for managing the risk of spring frosts in orchards.

The Czech Republic has experienced considerable temperature increases in recent decades (e.g. Zahradníček et al. 2021, 2022; Brázdil et al. 2022). In particular, the increases in winter and spring temperatures, contributing to the advanced occurrence of false springs and advanced phenology of fruit trees (e.g. Bauer et al. 2009; Černá et al. 2012), could enhance the risk of late spring frosts (e.g. Potop et al. 2013, 2014a) and their damaging effects (Hájková et al. 2023). To test this hypothesis, this study uses different sets of high-quality data to present the climatology of spring frosts, false springs and frost risk days in the Czech Republic during the period 1961–2021, explaining their circulation patterns based on objective classification, demonstrating changes in selected series of spring fruit-tree phenophases and characterising changes in fruit-tree production with respect to the effects of spring frosts. The aim of this paper is to enable a better understanding and to quantitatively describe and explain existing relationships.

2 Data

2.1 Meteorological data

To describe spring (March–May) frosts and false springs, homogenised daily temperature data recorded during the period 1961–2021 at 155 climatological stations of the Czech Hydrometeorological Institute from across the territory of the Czech Republic (hereafter CR) were used. Warm climate tree species (e.g. apricots or peaches) are generally grown at altitudes below 300 m a.s.l., while cherries or apples can be grown even at higher elevations, with some traditional varieties having a history of being grown even at 600 m a.s.l. (Blažek 1998). At the same time, the total extent of fruit orchards in the CR is relatively limited. Using two altitudinal intervals (Demek 1987) allowed us to split the related stations into two groups: (a) Group I: 55 stations with altitudes up to 300 m a.s.l. (landscape largely

consisting of lowlands and flat, hilly terrain) and (b) Group II: 100 stations with altitudes in the interval 301–600 m a.s.l. (areas represented mainly by flat and dissected hilly land) (Fig. 1). Positions above 600 m a.s.l. were not considered because they do not generally include productive areas for fruit trees or for intensive agriculture.

Based on long-term experience with homogenisation of climatological series (e.g. Štěpánek et al. 2011, 2013; Zahradníček et al. 2014; Squintu et al. 2020), the new homogenisation of Czech daily temperature series was realised in 2022 in three steps:

(a)   Quality control

MetQC software (Štěpánek et al. 2023), a part of the control of the European Climate Assessment & Dataset (ECA&D), was applied as a fully automated method of quality control of ECA&D. MetQC adds a station intercomparison allowing the detection of suspect values that fail to be identified by stand-alone tests of ECA&D.

(b)   Detection of breakpoints

Detection of breakpoints was performed for the monthly temperature series by applying the standard normal homogeneity test (SNHT) after Alexandersson (1986) and the bivariate test after Maronna and Yohai (1978). If a breakpoint was confirmed in the metadata, the empirical limit for adjustment (the ratio between the detection count and the number of theoretically possible detections) was set at 10% of all possible detections. If a detected breakpoint remained unexplained by the metadata, the limit was 15%.

(c)   Homogenisation

The adjustment of series was provided in a daily step using the distribution adjusting by percentiles (DAP) method, which is based on correction with the aid of individual percentiles, as derived from the method used in the correction of regional climate model outputs (Déqué 2007). Additionally, missing daily data in some series were
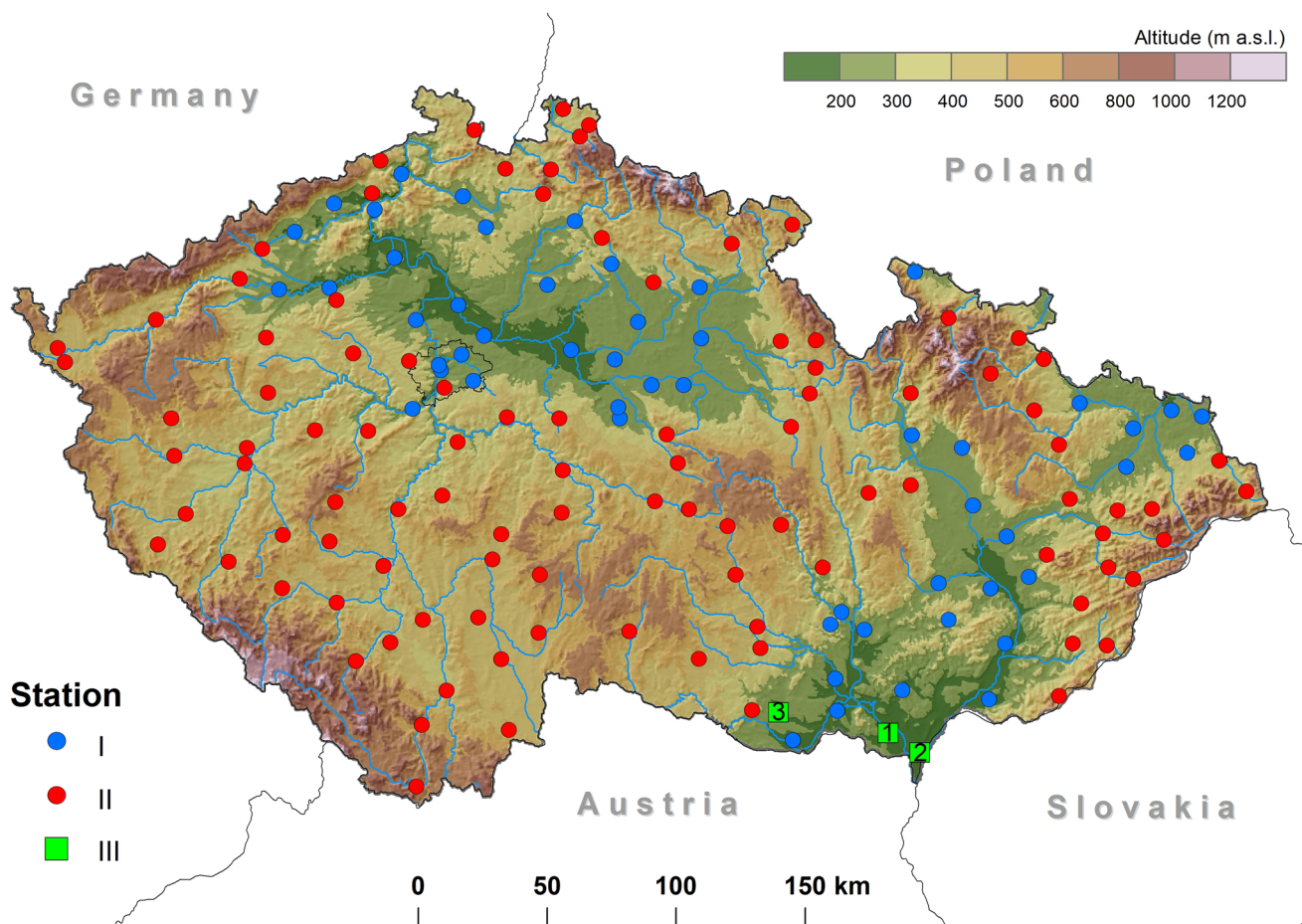

Fig. 1 Distribution of 155 climatological stations divided into two altitudinal groups (Group I: <301 m a.s.l., Group II: 301–600 m a.s.l.) and sites of phenological observations and apricot yield data (III: 1—Lednice, 2—Lanžhot, 3—southwestern Moravia) over the territory of the Czech Republic

complemented for the entire period 1961–2021 using interpolation and bias correction methods.

2.2 Circulation data

The objective classification of circulation types for the territory of the CR (Řehoř et al. 2021a, b) was used, based on principles first introduced by Jenkinson and Collison (1977). It was calculated for the geographic centre of the CR from the values of sea level pressure in the ERA5 reanalysis (Hersbach et al. 2020) based on the flow strength, flow direction and vorticity. Their threshold values were further used to define 27 circulation types, divided into nine anticyclonic, nine cyclonic and eight directional types, specified by the direction of airflow according to eight basic directions: anticyclonic types—A, AN, ANE, AE, ASE, AS, ASW, AW, and ANW; cyclonic types—C, CN, CNE, CE, CSE, CS, CSW, CW, and CNW; and directional types—N, NE, E, SE, S, SW, W, and NW. Days not attributable to any of the three groups were characterised as unclassified and included in type U (see Řehoř et al. 2021a, b for more details).

2.3 Phenological data

Despite there being a long tradition of phenological observations in the CR (Kurpelová et al. 1975; Brázdil et al. 2011), there were only a few available high-quality longterm series of fruit-tree phenophases for the first blossom and full blossoming at two locations in southeastern Moravia (see Fig. 1):

(a) Lednice: apple trees 1951–2000; apricot trees 1961–2021; cherry trees 1951–2009; pear trees 1951–2000.
(b) Lanžhot: pear trees 1951–2015.

Phenological observations were performed by only three observers during the whole period (Bartošová et al. 2022) in accordance with the methodology of the Czech Hydrometeorological Institute and related guidelines for phenological observations (Valter 1981).

2.4 Fruit-trees produce data

Broad information on fruit farming in the CR was collected and annually published in reports of the Ministry of Agriculture of the CR (MZČR 2023). The series of fruit tree produce, expressed as the value of the yield of the corresponding fruit in kilograms recalculated to one tree for seven main fruit tree types (apricot, peach, cherry, sour cherry, pear, apple, plum) were created from these annual reports for the 1996–2021 period for the entire CR. Apricot series from southwestern Moravia (the area between Znojmo and

Lechovice) for 2000–2021 complemented the above cited whole-country data.

3 Methods

A series of minimum daily temperatures (TMIN) for each of 155 climatological stations were used to select days with frost divided into five categories according to TMIN: (i) < 0.0 °C, (ii) < -1.5 °C, (iii) < -3.0 °C, (iv) < -4.5 °C and (v) < -6.0 °C. Using these selected days, the number of corresponding days in individual spring months (March, April, May), the entire spring (March–May) and from April to May as well as the latest spring dates of their occurrence for every year of the period 1961–2021 were calculated. These values were subsequently averaged for all 55 stations in Group I and separately for all 100 stations in Group II and were used to characterise the climatology of spring frosts in the CR.

A period of at least ten consecutive days with TMAX ≥ 10 °C was used in this paper to define false spring. Dates of first onsets for the false springs were calculated for each year of the period from 1961 to 2021 and were further used for calculation of "frost risk days" as the number of days between the beginning of the corresponding false spring and the date of the latest frost with TMIN < -1.5 °C. The number of frost risk days indicates the length of the period with a higher or lower potential for frost damage to fruit trees. Frost risk days were further used to create maps of frost risk day mean distribution over the territory of the CR for the entire period 1961–2021 as well as for individual decades. In addition to 155 cited stations (Sect. 2.1), an additional 30 stations located at altitudes above 600 m a.s.l. were used for the construction of related maps.

For the analysis of the relationships of frost day categories and false spring onset to circulation types of the objective classification defined in Sect. 2.2, absolute frequencies of circulation types for each individual station were calculated separately and then summed with other stations for Group I and Group II and transformed into relative frequencies of the individual circulation types.

To analyse linear trends in created time series, parameters of trends were estimated by applying the nonparametric Theil-Sen method, which is more robust to outliers (Sen 1968; Theil 1992). The presence of a significant linear trend ($p < 0.01$, $p < 0.05$ or $p < 0.10$) in the analysed series was evaluated using the Mann–Kendall test with the null hypothesis of no monotonic trend in the analysed series (Mann 1945; Kendall 1975). To analyse the relationship of fruit-tree yields to selected climate variables, Pearson correlation coefficients, tested for statistical significance ($p < 0.05$), were calculated.

4 Results

4.1 Climatology of spring frosts and false spring

4.1.1 Spring frosts

Fluctuations in the number of spring frost days of different frost categories (according to TMIN) for two altitudinal Groups I and II in the CR during the period 1961–2021 are demonstrated in Fig. 2a–e. Reflecting the temperature decrease with increasing altitude, the number of frost days in the five different categories was systematically higher in Group II than in Group I, despite their high interannual variability showing more or less parallel changes. The mean number of spring frost days decreased with increasing frost severity (Table 1) from 21.4 days for TMIN < 0.0 °C to 2.6 days for TMIN < −6.0 °C in Group I and from 27.3 days to 4.0 days in Group II. As expected, box plots showed higher values of median, upper

and lower quartile as well as both extremes (maximum and minimum) for Group II compared to Group I (Fig. 2f). Slightly lower variability of such values expressed by standard deviation (SD) in Group I compared to Group II appeared in all five frost categories (Table 1). Although the number of spring frost days decreased for all frost categories, it was statistically significant only for TMIN < 0.0 °C (−0.76 days/10 years, $p < 0.10$ in Group I; −1.19 days/10 years, $p < 0.05$ in Group II) and for TMIN < −4.5 °C (−0.55 days/10 years, $p < 0.10$ in Group II). Some significant decreasing trends in Group II were also recognised for April–May (Table 1) and for March and May (Table S1).

Spring circulation patterns in the CR during the period 1961–2021 were characterised by the highest occurrence of directional (35.9%) and anticyclonic (35.5%) types, while cyclonic types were less frequent (27.2%) (Table 2). For all categories of frost days in both altitudinal Groups I and II, proportions of anticyclonic types grew with increasing
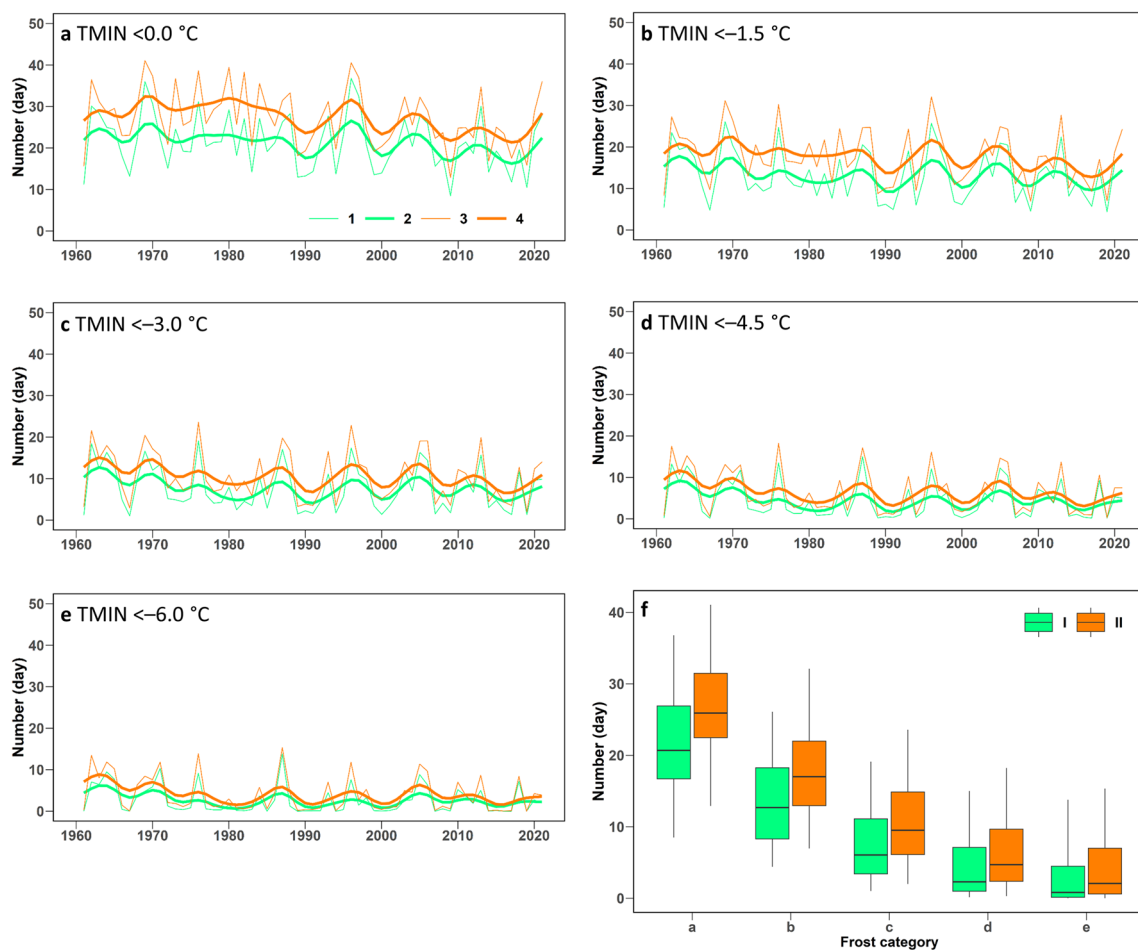

Fig. 2 Numbers of spring frost days of different frost categories (according to TMIN) in the Czech Republic during the period 1961–2021: **a–e** fluctuations in mean numbers of spring frost days in Groups I (1) and II (3), smoothed by a 10-year Gaussian filter (2,4); **f** box plots of the number of spring frost days for 55 stations in Group I and 100 stations in Group II

Table 1 Numbers of frost days of different frost categories (according to TMIN) in two altitudinal Groups I and II in spring (March–May) and April–May in the Czech Republic during the period 1961–2021

Group	Spring			April–May		
	MN	SD	LT	MN	SD	LT
TMIN < 0.0 °C						
I	21.4	6.5	−0.76*	6.1	3.0	−0.27
II	27.3	6.9	−1.19**	9.2	4.1	−0.46*
TMIN < −1.5 °C						
I	13.2	5.9	−0.50	2.9	2.0	−0.08
II	17.7	6.3	−0.74	4.7	2.6	−0.21
TMIN < −3.0 °C						
I	7.6	5.3	−0.44	1.2	1.2	−0.02
II	10.6	5.8	−0.68	2.0	1.6	−0.05
TMIN < −4.5 °C						
I	4.5	4.3	−0.29	0.4	0.6	−0.01
II	6.4	5.1	−0.55*	0.8	0.9	−0.00
TMIN < −6.0 °C						
I	2.6	3.3	−0.09	0.1	0.2	0.00
II	4.0	4.3	−0.32	0.3	0.4	0.00

MN mean number in days, *SD* standard deviation in days, *LT* linear trend in days/10 years

Statistical significance of LT: *$p < 0.10$, **$p < 0.05$

Table 2 Relative frequency (%) of three groups of circulation types (A—anticyclonic, C—cyclonic, D—directional) of the objective classification in frost days of different categories (according to TMIN) in two altitudinal Groups I and II in spring and April–May in the Czech Republic for the period 1961–2021 (all—includes all days without/with frost in spring and in April–May)

| TMIN (°C)	Spring						April–May					
	Group I			Group II			Group I			Group II		
	A	C	D	A	C	D	A	C	D	A	C	D
< 0.0	47.7	15.3	33.6	45.1	18.0	36.5	52.4	13.8	33.2	47.6	17.3	34.3
< −1.5	50.1	12.3	37.4	47.3	15.4	37.0	57.3	11.8	30.6	51.6	14.7	33.2
< −3.0	50.7	10.3	38.8	48.3	13.2	38.2	60.3	11.4	28.2	54.8	13.0	31.9
< −4.5	51.9	9.4	38.6	48.7	11.8	39.4	64.7	13.5	21.7	55.7	13.4	30.7
< −6.0	53.3	9.6	37.1	49.4	10.8	39.7	68.2	17.2	14.6	56.0	15.1	27.6
All	35.5	27.2	35.9	35.5	27.2	35.9	33.5	30.0	34.6	33.5	30.0	34.6

severity of frosts (I: from 47.7 to 53.3%, II: from 45.1 to 49.4%), while below-mean proportions of cyclonic days decreased. The proportions of directional types grew continuously for Group II but were less than 4%. From individual circulation types, central anticyclone A dominated, followed by eastern E and southeastern SE directional types and eastern anticyclonic type AE, and Group II was also dominated by northeastern type NE (Fig. 3). The frequency of type E was substantially amplified for more severe frosts (almost reaching the frequency of type A), while the frequency of the other mentioned types increased only slightly.

Narrowing the scope to frost days in April–May (Table 2), the time period to which the majority of late frosts belong, the dominant role of anticyclonic types further increased with increasing frost severity: in Group I from 52.4 to 68.2% and in Group II from 47.6 to 56.0%. The proportions of cyclonic and directional types were below their mean occurrences. Among the most frequent individual circulation types, A, NE and AE appeared, accompanied by the anticyclonic southeastern type ASE in Group I and the anticyclonic northeastern type ANE and type E in Group II (Fig. S1). However, in contrast to what occurred over the entire spring period, the frequency of eastern directional types decreased with a higher severity of frosts (particularly in Group I) in favour of type A, reaching as high as 30.5% frequency.

Fluctuations in the mean dates of the latest spring frosts (Fig. 4a–e) showed generally large interannual variability nearly parallel for both altitudinal Groups I and II with negative linear trends, i.e. their earlier occurrence. These mean dates of the latest spring frosts changed for five frost

Fig. 3 Relative frequency (%) of individual circulation types of the objective classification in spring frost days of different frost categories (according to TMIN) in Groups I and II for the Czech Republic in the period 1961–2021
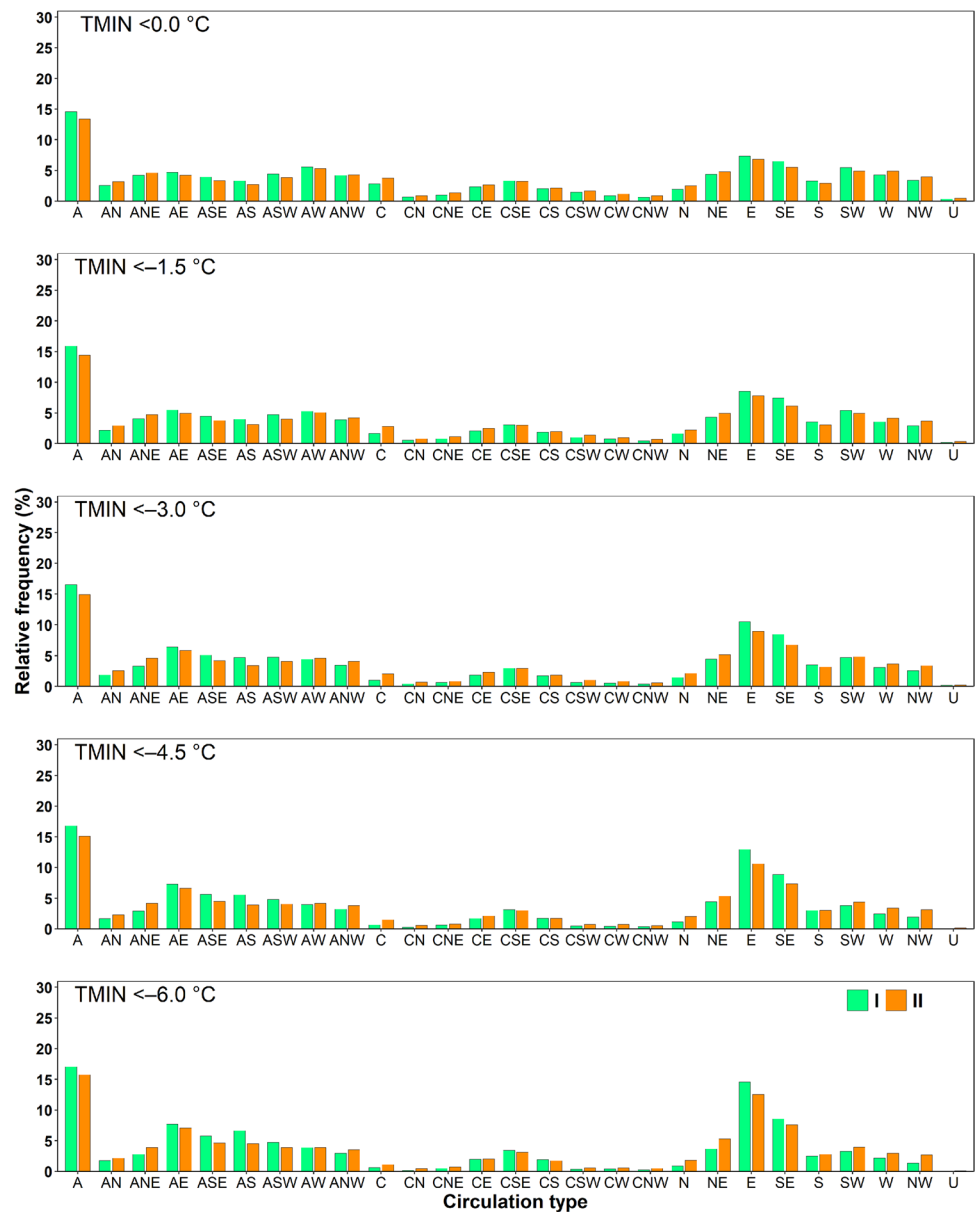
categories between 2 March and 23 April in Group I and between 10 March and 1 May in Group II (Table 3). As expected, the box plots displayed a shift to later dates in the median and the upper and lower quartiles as well as in extremes in Group II compared to Group I (Fig. 4f). However, the standard deviations showed slightly less variability for the first two categories in Group I than in Group II, but for three other categories, the opposite was observed (Table 3). There was also great variability in the dates of the earliest and latest frost occurrences, which fluctuated for the five selected frost categories between January and May. Linear trends in dates of the latest spring frosts for all frost categories and both altitudinal intervals showed their earlier onset at approximately 1 and 2 days per 10 years, but a statistically significant decline was recorded only for Group II in the first two frost categories: for TMIN < 0.0 °C, it was −1.56 days/10 years, $p < 0.10$, and for TMIN < −1.5 °C, it was −1.18 days/10 years, $p < 0.05$.

4.1.2 False spring

False spring started in the CR on average on 2 April in Group I and on 9 April in Group II during the period 1961–2021 (Table 4). It showed great interannual variability with a broad range between the earliest and latest onsets, namely, between 9 March and 2 May in Group I (range of 55 days) and between 17 March and 8 May in Group II (range of 53 days). The variability of onsets expressed by standard deviation was higher in Group II than in Group I. For long-term fluctuations in interannual variability (Fig. 5),
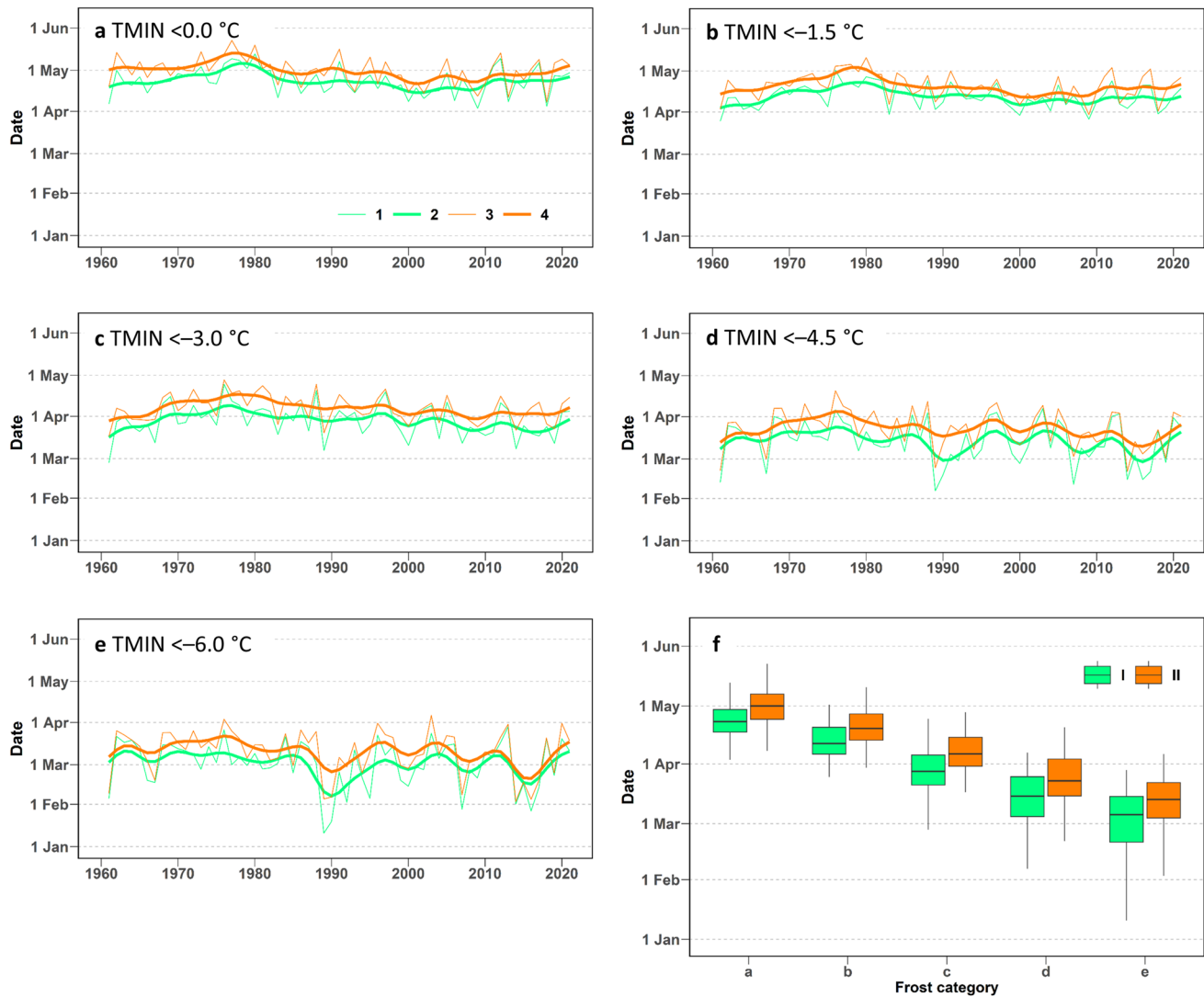
Fig. 4 Dates of the latest spring frosts of different frost categories (according to TMIN) in the Czech Republic during the period 1961–2021: **a–e** fluctuations in mean date of the latest spring frosts in Groups I (1) and II (3), smoothed by a 10-year Gaussian filter (2,4); **f** box plots of dates of the latest spring frosts for 55 stations in Group I and 100 stations in Group II

the earliest onsets around the mid-1970s followed a sudden delay to 1980, while from that time, a generally decreasing tendency (i.e. earlier onsets of false spring) in smoothed values appeared. While the linear trend for the whole series was significantly decreasing only for Group II with −2.04 days per 10 years, $p < 0.05$ (Table 4), significantly more advanced onset was identified from 1980 in both groups (I: −3.92 days/10 years, $p < 0.05$; II: −4.94 days/10 years, $p < 0.01$).

Concerning circulation patterns associated with the onset of a false spring (Fig. 6), type A again experienced the highest frequency (I: 24.3%, II: 21.6%); however, it was complemented by anticyclonic western (AW), western (W), and anticyclonic southwestern (ASW) patterns, and Group II also had a southeastern (SE) pattern. This indicates that the

western airflow was therefore similar to anticyclonic patterns in importance, while the northern and northwestern airflows almost did not occur.

The onsets of false springs can be complemented by frost risk days, demonstrating the potential number of days when frost with TMIN < -1.5 °C can appear after the onset of false springs. Positive values mean that a frost appeared after the beginning of false spring and vice versa. Both altitudinal groups experienced nearly the same means (11.6 and 11.5 days, respectively) and variability (standard deviations 13.9 and 14.3 days, respectively) during the period from 1961–2021. The highest numbers of frost risk days in Group I were recorded in 1981 and 2012 (39.3 and 38.6 days, respectively), while in Group II, they were also recorded in 2012 (46 days), followed by 2017 (37.2 days) (Fig. 7). The

Table 3 Statistical characteristics of dates of the latest spring frosts for their different categories (according to TMIN) in two altitudinal Groups I and II in the Czech Republic during the period 1961–2021

Group	MD	SD	ED	LD	LT
TMIN < 0.0 °C					
I	23 April	9.2	3 April 2009	13 May 1980	−0.89
II	1 May	9.8	8 April 2018	23 May 1977	−1.56*
TMIN < −1.5 °C					
I	12 April	8.5	25 March 1961	2 May 1976	−0.65
II	19 April	9.5	30 March 2009	11 May 1980	−1.18**
TMIN < −3.0 °C					
I	28 March	11.6	27 February 1961	24 April 1976	−1.24
II	7 April	9.5	17 March 1961	28 April 1976	−1.08
TMIN < −4.5 °C					
I	14 March	15.3	7 February 1989	7 April 2003	−1.59
II	23 March	13.3	21 February 2014	20 April 1976	−1.43
TMIN < −6.0 °C					
I	2 March	17.4	11 January 1989	29 March 2013	−1.48
II	10 March	15.8	3 February 2014	6 April 2003	−1.54

MD mean date, *SD* standard deviation in days, *ED* the earliest day, *LD* the latest day, *LT* linear trend in days/10 years

Statistical significance of LT: *$p < 0.10$, **$p < 0.05$

Table 4 Statistical characteristics of the onset of false spring in two altitudinal Groups I and II in the Czech Republic during the period 1961–2021

Group	MD	SD	ED	LD	LT
I	2 April	12.4	9 March 2002	2 May 1980	−1.49
II	9 April	15.6	17 March 1990	8 May 1980	−2.04**

MD mean date, *SD* standard deviation in days, *ED* the earliest day, *LD* the latest day, *LT* linear trend in days/10 years

Statistical significance of LT: **$p < 0.05$
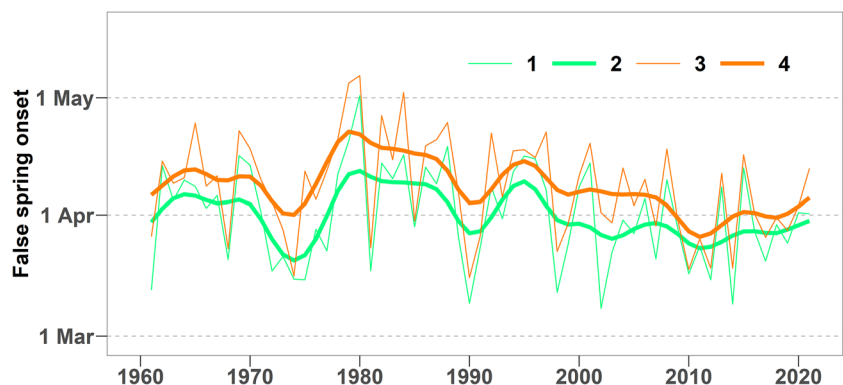
most compact periods of higher annual numbers of frost risk days occurred during the period 1971–1978, accompanied by other peaks in approximately 1990 and in the early 2010s. Both altitudinal groups showed slightly increasing nonsignificant linear trends, 0.69 days/10 years in Group I and 0.30 days/10 years in Group II.

Figure 8 shows the spatial distribution of frost risk days over the territory of the CR for the period 1961–2021 and its individual decades. Over the entire period, the highest proportions across the CR territory were attributed to intervals of 10–20 frost risk days (48.6%) and 0–10 days (44.2%) (Table 5). While in the starting decade of 1961–1970, such days occurring up to 10 days after false spring onset covered three quarters (75.4%) of the territory, in 2011–2020, the largest area of 58.0% met the interval of 10–20 days and 30.7% to 20–30 days, demonstrating an increasing risk of spring frosts. A spatial frost risk distribution similar to that of the period 2011–2020 appeared from 1971 to 1980, while the spatial patterns of the three decades between 1981 and 2010 were closer to those of the period 1961–1970. The proportions of areas with the latest frosts occurring before false spring onset (i.e. negative values of frost risk days) increased from 1.3% (2011–2020) to 15.8% (1991–2000). Relative proportions calculated for the entire territory of the CR were complemented by proportions calculated separately for the two altitudinal Groups I and II and are depicted in Fig. S2.

In addition to the number of frost risk days after the onset of a false spring (Fig. 8), the probability of the occurrence of frost days with TMIN < −1.5 °C after 10 days (with TMAX ≥ 10 °C) from that false spring onset provides additional information about frost danger for fruit trees (Fig. 9). Generally, an area with higher frost probability has a higher likelihood of fruit trees being potentially damaged by late spring frosts. A frost probability between 40 and 50% corresponds to the greatest part (43.4%) of the CR, and a probability higher than 50% affects 36% of the Czech territory (29.2% corresponds to a probability between 50 and 60%). At lower altitudes up to 300 m (Group I), the probability of 50–60% covers 43.7%, while at higher altitudes 301–600 m
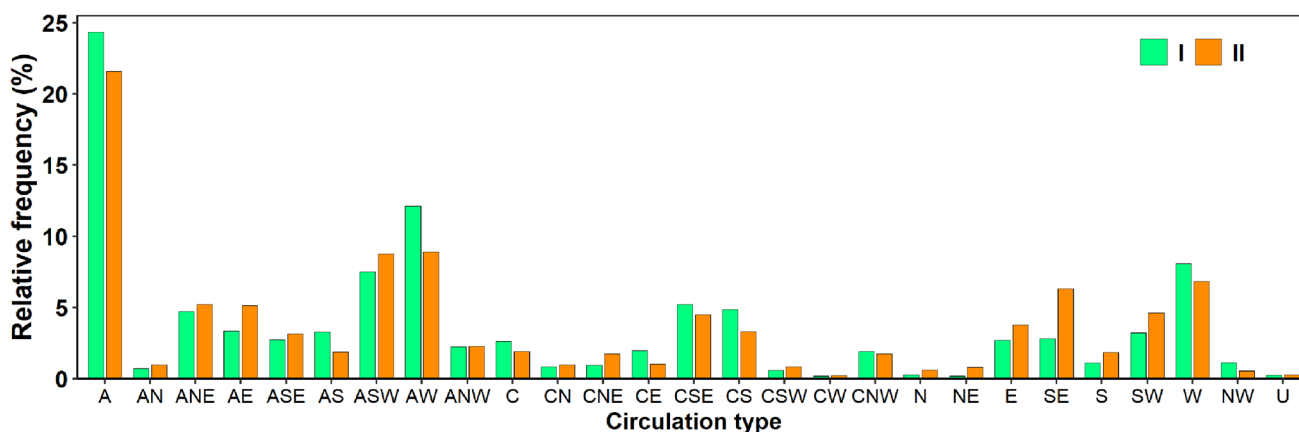
Fig. 5 Fluctuations in the onsets of false springs in the Czech Republic for Groups I (1) and II (3) in the period 1961–2021. Smoothed by a 10-year Gaussian filter (2, 4)

Fig. 6 Relative frequency (%) of individual circulation types of the objective classification for the first day of false spring for Groups I and II in the Czech Republic during the period 1961–2021

Fig. 7 Fluctuations in the number of frost risk days (columns) in Groups I and II in the Czech Republic during the period 1961–2021. Smoothed by a 10-year Gaussian filter (bold lines)
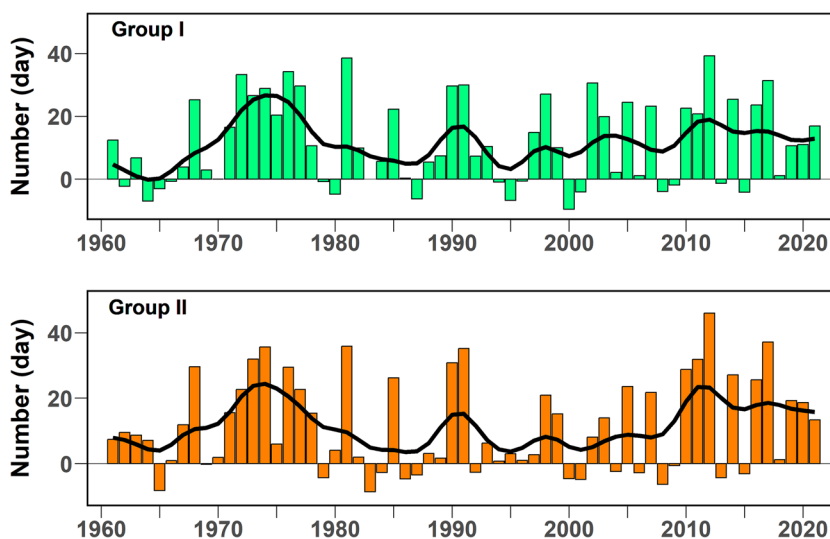
(Group II), the probability was 51.3% for frost probability 40–50%. The mean value of the frost probability at altitudes up to 300 m was 52.3% and between 300 and 600 m was 46.8%. Highly endangered areas are particularly lower positions in southeastern Moravia with important production of apricots and peaches, as well as similar lower positions in the greater parts of Bohemia.

4.2 Spring phenology of fruit trees

Fluctuations in the dates of the phenophases "first blossom" and "full blossoming" for a few fruit trees in Lednice and Lanžhot (southeastern Moravia) are documented in Fig. 10. In addition to a large interannual variability of all series, they were characterised by decreasing linear trends expressing the earlier onsets of these two phenophases. These trends were

not statistically significant only in Lednice for both phenophases of pear and for the first blossom in apple (Table 6). Both phenophases of all trees occurred in April with a few days of difference from apricot (the earliest onset) to cherry and pear to apple (the latest onset).

To show the consistency of the onsets of the two phenophases with false springs and late frosts, all graphs in Fig. 10 were enhanced by circles corresponding to these two climatic variables and calculated for the Lednice station. Climatic data from Lednice were further used for the pear-tree series at Lanžhot with respect to the small distance of two places (*c*. 15 km) and small difference in altitude between them (*c*. 10 m). The phenophase first blossom was delayed to the onset of false spring on average by only 12.4 days for apricot trees, while the longest delay was 54 days in 1998, but in 1994, the first blossom started 15 days

Fig. 8 Spatial distribution of mean numbers of frost risk days occurring after the false spring onset over the territory of the Czech Republic in the period 1961–2021 and in individual decades
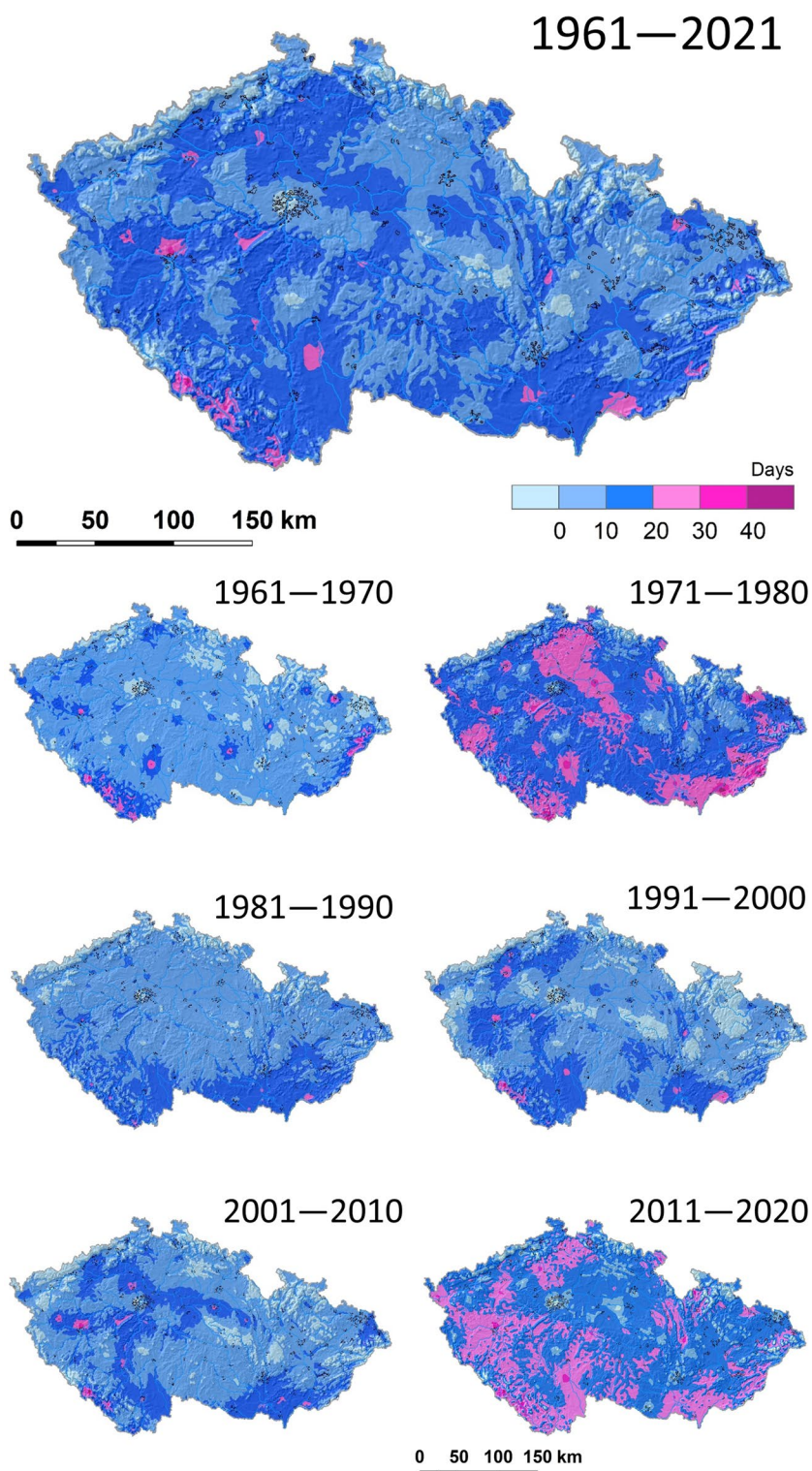
earlier (Table S2). For cherry trees, the average delay was 17.8 days, and for pear trees, it was 25.2 days. On the other hand, apple trees started to blossom on average 28.8 days after false spring beginning with an extreme delay between 59 days in 1975 and 5 days in 1956. A late beginning for blossoming decreases the risk of late frosts. In the series

analysed, such risk was highest for apricot trees (42.6% of years, when late frosts occurred after the first blossom), followed by cherry trees (39.0%), while for pear trees, it was 26.0% at Lednice and 23.1% at Lanžhot and only 16.0% for apple trees. In the remaining portion of the years, the onset of late frosts was earlier than that of first blossoms.

Table 5 Mean spatial proportions (%) of selected intervals of numbers of frost risk days occurring after the false spring onset over the territory of the Czech Republic during the period 1961–2021 and in individual decades

Period	Interval of numbers of frost risk days					
	>40	30–40	20–30	10–20	0–10	<0
1961–1970	0.0	0.1	1.4	10.8	75.4	12.3
1971–1980	0.1	1.6	24.4	56.3	15.2	2.4
1981–1990	0.0	0.0	0.2	24.4	68.8	6.6
1991–2000	0.0	0.1	1.4	26.4	56.3	15.8
2001–2010	0.0	0.1	1.2	28.3	58.1	12.3
2011–2020	0.0	0.7	30.7	58.0	9.3	1.3
1961–2021	0.0	0.1	2.3	48.6	44.2	4.8
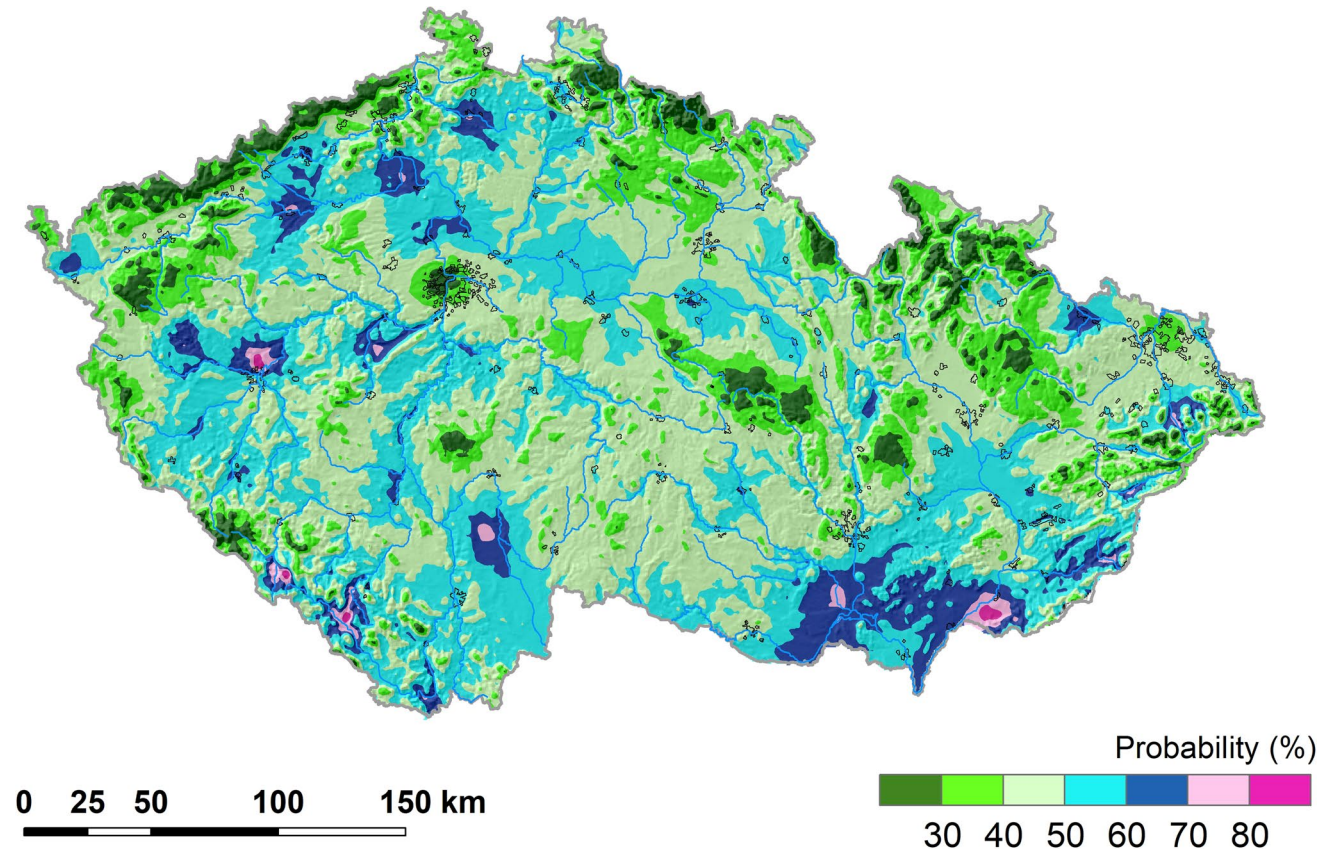
Fig. 9 Spatial probability (%) of a day with TMIN < −1.5 °C occurring 10 days after the beginning of false spring in the Czech Republic during the period 1961–2021

4.3 Fruit tree production and spring frosts

Figure 11 shows the annual whole-country yields of key fruit trees in the CR during the 1996–2021 period. Corresponding series reflect, in addition to a great interannual variability of individual yields, a variety of different linear trends. Statistically significant trends exhibited only two trees: plum trees increasing (3.1 kg/tree per 10 years, $p < 0.01$) and cherry trees decreasing (−0.85 kg/tree per 10 years, $p < 0.05$). All other linear trends were statistically nonsignificant: more or less zero for sour cherry trees, increasing for pear trees

and decreasing for apricot, peach and apple trees (Table 7). Remarkably different trends for plums can be attributed to the fact that plum production might have helped a much faster rate of replanting required for plums and an inherently better chance to cope with changing climate and pest-disease challenges. Except for the yields of plum trees, the yields of apricot trees with the earliest spring blossoming were the most variable according to standard deviation. The lowest yield for apricot in 2002 was related to frost in early April, accompanied by rain and snow showers, which created good conditions for the spread of twig canker. Although

Fig. 10 Fluctuations in dates of the phenophase **a** first blossom and **b** full blossoming in southeastern Moravia between 1951 and 2021 (Lednice: apricot tree, cherry tree, pear tree, apple tree; Lanžhot: pear tree). Circles show onsets of false spring and occurrences of the last spring frost for TMIN < −1.5 °C
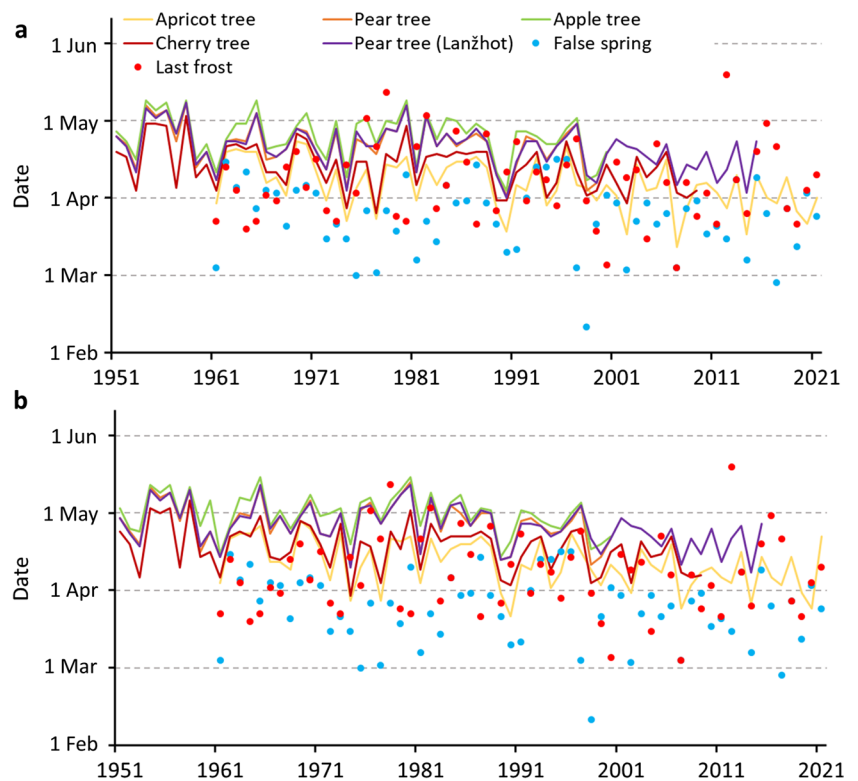

Table 6 Statistical characteristics of the onsets of first blossom and full blossoming of selected fruit trees for Lednice and Lanžhot in southeastern Moravia between 1951 and 2021

Tree	First blossom					Period
	MD	SD	ED	LD	LT	
Lednice						
Apricot	5 Apr	9.6	12 Mar 2007	22 Apr 1969	−2.3***	1961–2021
Cherry	12 Apr	9.1	25 Mar 1977	2 May 1958	−2.0***	1951–2009
Pear	21 Apr	8.8	1 Apr 1990	7 May 1958, 1980	−1.2	1951–2000
Apple	24 Apr	8.8	3 Apr 1990	8 May 1954, 1958, 1965, 1980	−1.4	1951–2000
Lanžhot						
Pear	19 Apr	8.5	31 Mar 1990	7 May 1958	−1.7**	1951–2015

Tree	Full blossoming					Period
	MD	SD	ED	LD	LT	
Lednice						
Apricot	10 Apr	9.2	21 Mar 1990	27 Apr 1969	−2.2***	1961–2021
Cherry	17 Apr	8.8	29 Mar 1974	5 May 1958	−1.8**	1951–2009
Pear	26 Apr	8.3	10 Apr 1975, 1998	12 May 1980	−1.3	1951–2000
Apple	30 Apr	7.6	13 Apr 1989	14 May 1965, 1980	−1.7**	1951–2000
Lanžhot						
Pear	25 Apr	8.2	7 Apr 2014	11 May 1965, 1980	−1.7**	1951–2015

MD mean date, *SD* standard deviation in days, *ED* the earliest date, *LD* the latest date, *LT* linear trend in days/10 years

Statistical significance of LT: ** $p < 0.05$, *** $p < 0.01$

its occurrence is not directly related to frost, it often occurs simultaneously with spring frosts because high air humidity is favourable for its spread. Damaging late frosts were also recorded in other years with the lowest yields of other fruit trees, such as in 2010 (sour cherry), 2011 (apple), 2013 (cherry), 2016 (peach), 2017 (pear) and 2020 (cherry).

Taking into account the 5 years with the lowest yields for each fruit tree (except plum), all of them
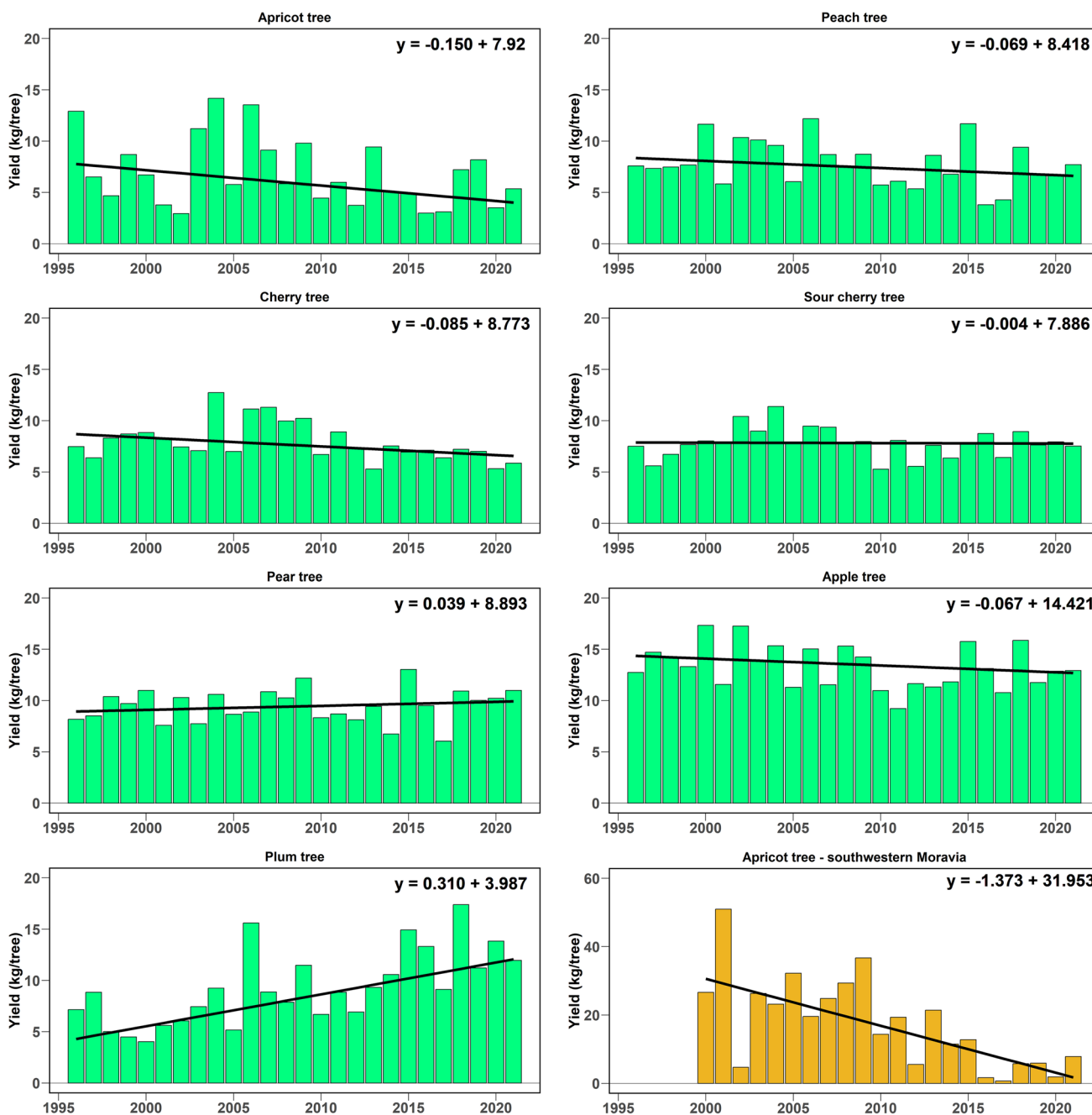
Fig. 11 Fluctuations and linear trends in the annual whole-country yields (kg/tree) of seven selected fruit trees in the Czech Republic during the period 1996–2021 and apricot-tree yields in southwestern Moravia during the period 2000–2021: Right above—equations of linear trends

were particularly affected in 2017, when the first wave of strong frost on 21 April damaged trees with advanced phenophases in southern Moravia and the second wave on 10 May damaged fruit trees across the whole country. Similarly, two waves of frosts on 9 April and on 18 May damaged fruit trees (except for apple and plum trees) in 2012. The low production of fruits in 2010 (particularly for peach, cherry, sour cherry and apple) was influenced by sudden cooling during fruit blossoming and strong

rain spells in May, which resulted in insufficient pollination with subsequent extension of diseases (scab and twig canker).

In good agreement with the whole-country apricot-tree series is also a local series from southwestern Moravia, showing very strong statistically significant decreasing trends (−13.7 kg/tree per 10 years, $p < 0.01$). The years of lowest yields clearly attributed to late spring frosts agreed with those reported above in the order 2017 (only 0.7 kg/

Table 7 Statistical characteristics of the whole-country yields (kg/tree) of selected fruit trees in the Czech Republic for the 1996–2021 period

Tree	Mean	SD	Maximum		Minimum		LT
			Yield	Year	Yield	Year	
Apricot	6.9	3.3	14.2	2004	2.9	2002	−1.50
Peach	7.8	2.2	12.2	2006	3.8	2016	−0.69
Cherry	7.9	1.9	12.7	2004	5.3	2013, 2020	−0.85**
Sour cherry	7.9	1.4	11.4	2004	5.3	2010	−0.04
Pear	9.5	1.6	13.0	2015	6.0	2017	0.39
Apple	13.3	2.1	17.3	2000, 2002	9.2	2011	−0.67
Plum	9.3	3.6	17.4	2018	4.0	2000	3.10***

SD standard deviation, *LT* linear trend in kg/tree per 10 years

Statistical significance of LT: **$p < 0.05$, ***$p < 0.01$

tree), 2016 (1.7 kg/tree) and 2020 (1.9 kg/tree), followed by 2002, 2012, etc. (Fig. 11). On the other hand, the highest disagreement exists for the year 2001, indicating the highest yield of 51 kg/tree in southwestern Moravia, while the whole-country apricot series indicated very low yield, as well as the series of peach, pear, apple and plum.

The potential effects of spring frosts on the Czech whole-country annual yields of the seven selected types of fruit trees during the 1996–2021 period were analysed using Pearson correlation coefficients (Table 8). Statistically significant negative correlations (according to *t* test, $p < 0.05$) between fruit-tree yields and climate variables, confirming the effects of frosts on yields, were found for dates of late spring frosts (LF), frost risk days (RD) and temperature sums of days between the onset of false spring and last frost (TS) for both altitudinal Groups I and II. All these climate variables were significantly correlated with apricot, peach, pear and apple yields (for apple, a positive correlation with false spring onset in Group II also appeared with a value of 0.42). For sour cherry, significant correlations were calculated with LF-II, RD-II and TS-I, while for cherry, significant correlations were found only with LF-I. None of the selected climate variables were significantly correlated with plum tree yields. The highest correlations with all variables

were found for peach, while for pear tree, they were more or less the same, fluctuating only between −0.44 and −0.47. The relationship of yields to corresponding variables with the highest correlations for each fruit tree analysed (except plum) was expressed by a correlation graph with a regression line in Fig. 12. Although correlation analysis demonstrated a clear imprint of spring frosts on the yields of selected fruit trees, these results explained only a small part of the total variability.

5 Discussion

Statistically significant increases in mean, minimum and maximum temperatures in the CR since 1961 (Zahradníček et al. 2021; Brázdil et al. 2022) were reflected in the characteristics of frost days and false springs in this study. The number of frost days (TMIN < 0.0 °C) showed statistically significant decreases for the entire spring (which is in agreement with Zahradníček et al. 2022), but only for Group II in April–May and in spring for TMIN < -4.5 °C (Table 1). Connecting these results with trends for individual spring months in Table S1, only 16% of all series experienced statistically significant decreasing trends. Concerning the series

Table 8 Pearson correlation coefficients between yields of selected fruit trees and climate variables in the Czech Republic during the 1996–2021 period

Tree	LF-I	LF-II	RD-I	RD-II	TS-I	TS-II
Apricot	**−0.38**	**−0.46**	**−0.47**	**−0.47**	**−0.47**	**−0.51**
Peach	**−0.58**	**−0.70**	**−0.53**	**−0.68**	**−0.67**	**−0.59**
Cherry	**−0.44**	−0.37	−0.27	−0.28	−0.22	−0.20
Sour cherry	−0.37	**−0.42**	−0.29	**−0.44**	**−0.42**	−0.32
Pear	**−0.46**	**−0.47**	**−0.45**	**−0.47**	**−0.44**	**−0.45**
Apple	**−0.46**	**−0.60**	**−0.42**	**−0.64**	**−0.67**	**−0.51**
Plum	−0.11	−0.14	−0.22	−0.15	−0.12	−0.22

Significant correlation coefficients for $p < 0.05$ according to *t* test are in bold

Climate variables: LF-I (LF-II)—date of the last spring frost with TMI < -1.5 °C in Group I (Group II); RD-I (RD-II)—number of frost risk days in Group I (Group II); TS-I (TS-II)—temperature sum of days between onset of false spring and last frost in Group I (Group II)
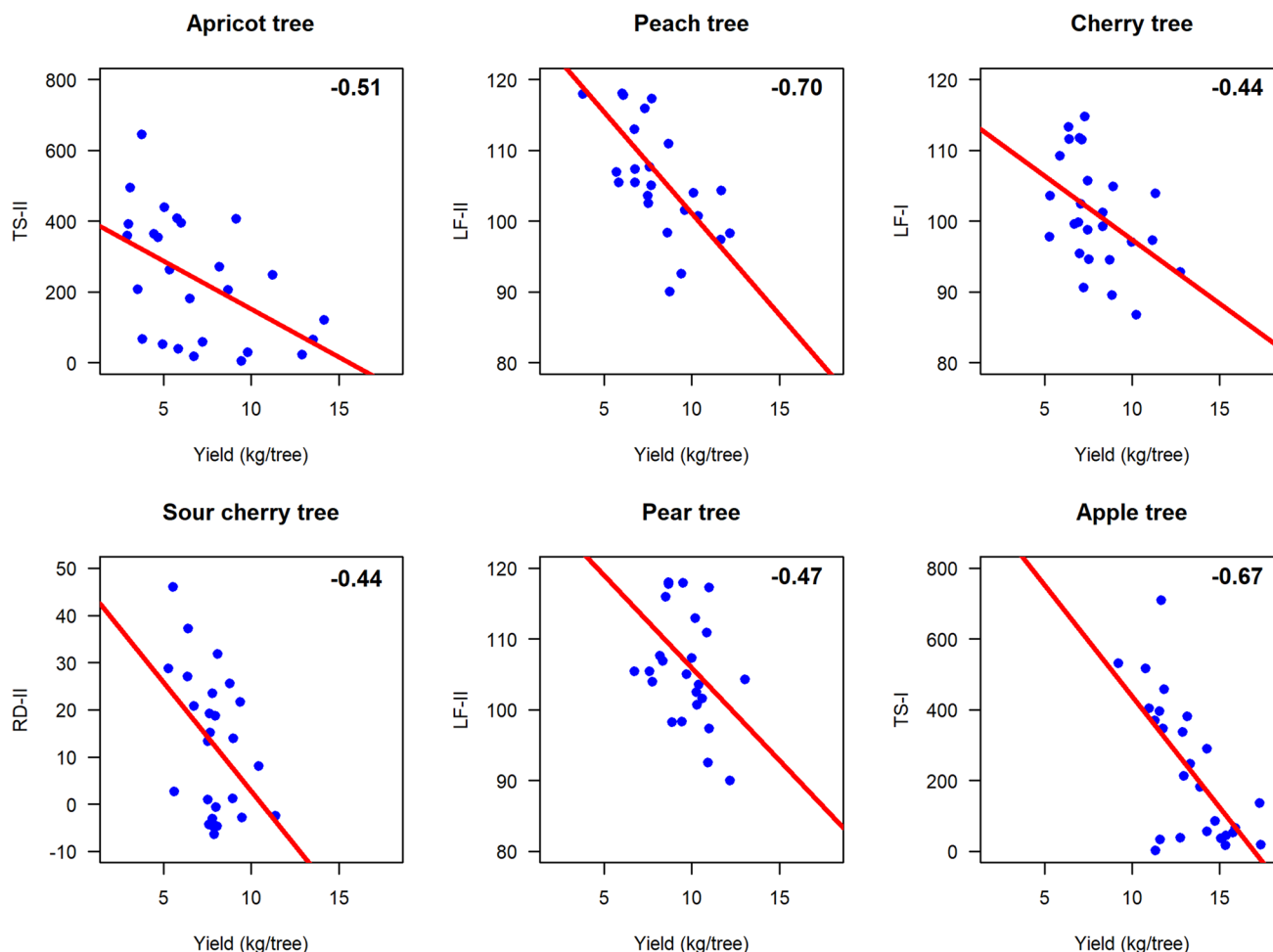
Fig. 12 Correlation fields and related regression lines between annual whole-country yields of fruit trees and selected climate variables for Groups I and II with the highest Pearson correlation coefficients (top right) of each fruit tree during the period 1996–2021 in the Czech Republic (LF, date of the last spring frost with TMIN < −1.5 °C; RD, number of frost risk days; TS, temperature sum of days between onset of false spring and the last frost)

of the dates of latest frosts (Table 3), despite their general earlier onset, only for Group II was it statistically significant for thresholds TMIN < 0.0 °C and TMIN < −4.5 °C (i.e. in 20% of all cases). Group II also indicated a significantly earlier onset of false spring, importantly accelerating from 1980 until the present in both altitudinal groups. These results are consistent with the findings of studies presented in papers dealing with similar topics, such as in the USA (Easterling 2002), Poland (Graczyk and Szwed 2020; Koźmiński et al. 2023) and central and southeastern Europe (Chervenkov and Slavov 2022).

Concerning the circulation patterns on days with spring frosts in the CR (Table 2), anticyclonic circulation types predominated directional types and particularly cyclonic types. This is in agreement with Wypych et al. (2017), who underlined the importance of anticyclonic situations for frost occurrence in Central Europe. They particularly reported the situation with an extensive high pressure system over Belarus and eastern Ukraine that caused an inflow of cold, continental air masses. In the analysis of circulation types on frost days, the day before the frost day should also be considered. Namely, the sea level pressure data used in the classifying process (see Sect. 2.2) are daily means, while minimum temperature usually occurs in the morning hours, i.e. circulation of the preceding day may also play an important role. Therefore, the frequencies of circulation types on days before the TMIN were calculated (Fig. S3). Compared to what is presented in Fig. 3, the relative frequencies of types NE, E, ANE and AE substantially increased, while for the remaining anticyclonic types, they decreased. This confirms a general expectation that spring frosts are often a result of a cold airflow followed by anticyclone occurrence in the Central European area, causing reduced cloud cover and lower wind speeds, amplifying radiation cooling in a layer of air at the surface.

Increasing spring temperatures were also reflected in earlier onsets of related phenophases of fruit trees, such as those documented for the first blossom and full blossoming of apricot, peach, pear and apple trees in southeastern Moravia (cf. Fig. 10 and Table 6). This has been confirmed by the findings of other studies in the CR (e.g. Bauer et al. 2009; Černá et al. 2012), creating favourable conditions for the damaging effects of late spring frosts (e.g. Potop et al. 2013, 2014a). Many studies have also demonstrated the increasing risk potential of late spring frosts to individual fruit trees such as cherry trees (Matzneller et al. 2016; Chmielewski et al. 2018; Demirsoy et al. 2022; Hájková et al. 2023; Hulsmann et al. 2023), cherry and apple trees (Vitasse et al. 2018), apple trees (Pfleiderer et al. 2019; Cebulj et al. 2022) and peach trees (Çetinbaş et al. 2021). On the other hand, some papers also reported lower frost risk or unchanged risk in some regions in Italy (Eccel et al. 2009) or Switzerland (Vitasse et al. 2018).

Early false springs in synergy with late frosts can cause great economic damage. For example, Labe et al. (2017) cited for the USA such early onset of false spring in 2012 with agricultural losses of $500 million in Michigan only. In Europe, the most dramatic economic losses of €3.3 bn caused by late spring frosts were recorded in 2017, particularly for fruit and wine, when Italy, France, Germany, Poland, Spain and Switzerland were the most affected countries (Faust and Herbold 2018; Vitasse and Rebetez 2018). In the Czech whole-country fruit yields from 1996–2021 (cf. Figure 11), the 2017 year brought—due to two waves of late frosts—the lowest yields for pear, the second lowest for peach and the third lowest for apricot trees (but the lowest for apricot in southwestern Moravia during 2000–2021). However, low yields of fruits in the CR caused by late spring frosts were also recorded for many other years. For example, for only 8 years (2003, 2004, 2006, 2009, 2010, 2013, 2015 and 2018) during the 2002–2021 period, any spring frosts damaging fruit trees were not reported according to the annual reports of the Ministry of Agriculture of the CR (MZČR, 2023).

Exposure of fruit trees to spring frost damage can be modified by different factors. Drepper et al. (2022) presented a broad systematic review of existing strategies used to manage the risk of spring frosts in orchards. Concerning the protection of fruit trees during flowering against frost, generally two basic ways exist: heating the air to a temperature of approximately 0 °C or creating conditions to reduce the effective radiation, and temperatures do not drop significantly below 0 °C. There are different protection outcomes with both methods. A uniform procedure has been developed in the past, but the financiers played the main role. In cases of more than two occurrences of spring frosts, the measures were rather economically ineffective. Concerning the CR, the protection of orchards against late frost is only partly possible, with only approximately one-third of ~ 16,000 ha of orchards being equipped with irrigation.

The (late) spring frosts and their damaging effects on plants in the twenty-first century belong to frequent scientific topics in many studies based on different types of climate scenarios from IPCC reports. For example, SRES scenarios (Special Report on Emission Scenarios) were used for Italy (Eccel et al. 2009) and six regions of Europe (Jönsson and Bärring 2011), RCP scenarios (Representative Concentration Pathways) for Germany (Chmielewski et al. 2018) and Switzerland (Lhotka and Brönnimann 2020), or SSP (Shared Socioeconomic Pathways) scenarios for Iran (Helali et al. 2022). With regard to the observed trends in late frosts, false springs and phenophases of fruit trees in the CR, an enhanced risk of frost damage to fruit trees can be expected in the future. Based on 12 simulations of RCM models (EURO-CORDEX 11 km) and three RCP scenarios (RCP2.6, RCP4.5 and RCP8.5), the projected temperature increase to the mid-twenty-first century may reach 1.5–2.4 °C for winter and 1.1–1.5 °C for spring (Štěpánek et al. 2019). This will contribute to earlier onsets of false springs, larger temperature sums and earlier beginnings of fruit-tree phenophases. Spring temperature increases will decrease the mean number of frost days for the CR to only 15–19 days in this season, but with the earlier occurrence of late frosts (e.g. in the Bohemian Plateau by ≥ 12 days—Potop et al. 2014b). Despite existing knowledge concerning this topic in the CR, new projections of late frosts, false spring, spring phenophases and potential damaging effects on fruit trees for new CMIP6 and SSP scenarios remain one of the upcoming research challenges.

6 Conclusion

The results of the analysis of spring frosts and their impacts on fruit trees in two altitudinal groups of the Czech Republic during the period 1961–2021 can be summarised as follows:

(a) The number of frost days for March, April, May, April–May and the entire spring (March–May), divided into five frost categories according to TMIN, exhibited decreasing linear trends, but only 16% of them were statistically significant. Similarly, in decreasing trends of dates of the latest spring frosts only 20% of them were statistically significant.

(b) False springs exhibited decreasing linear trends (i.e. earlier onset), which were statistically significant only for Group II. Related linear trends from 1980 until the present were much stronger and significant in both altitudinal groups. Nonsignificant increasing linear trends were found in the series of frost risk days.

(c) The occurrence of frost days was attributed particularly to the above-mean frequency of anticyclonic circulation types with their growing proportions with increasing frost severity, while deeply below-mean were frequencies of cyclonic types. Frosts were attributed particularly to central anticyclone type A and types with northeastern (NE, ANE), eastern (E, AE) and southeastern airflow (SE). The onset of false spring was particularly related to type A and types with western and southwestern airflow (AW, W, ASW).

(d) Statistically significant earlier onset of phenophases of first blossom and full blossoming were found in local series for apricot, cherry, pear and apple trees in southeastern Moravia. The damaging effects of late spring frosts were well reflected in years with low whole-country fruit yields during the 1996–2021 period, although they explained only part of the yield variability. Fruit trees were particularly affected in years with two waves of late spring frosts, for instance, in 2017 or 2012.

Knowledge about the dynamics of spring frosts in relation to the proven warming at the end of winter is an important factor in maintaining areas of fruit orchards. At the same time, it is an important factor for guiding directions in breeding and new technologies.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s00704-023-04671-2.

Declarations

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