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Air Frosts in Poland in the Thermal Growing Season (AT > 5 °C)

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Abstract: Frosts cause damage to plants in field crops and also trees, thus contributing to heavy economic losses in agriculture. One of the consequences of climate warming is the lengthening of the thermal growing season (AT > 5 °C) and acceleration of phenological phases as well as the lengthening of the frost-free period. This favourable element allows the extension of the range of cultivated plants to include plants requiring warmth and a longer development period. The present study concerns the area of Poland. The data on mean and minimum 24-h period air temperature (200 cm above ground level) were obtained from 52 meteorological stations of the Institute of Meteorology and Water Management—National Research Institute (IMGW-PIB) for the period 1971–2020. A day with air frost was identified when the recorded minimum air temperature was below 0.0 °C and the mean 24-h period air temperature was above 0.0 °C. All calculations concerning frosts were limited to the period with mean 24-h period air temperature >5 °C (the growing season) as determined with the Gumiński method. The obtained results show that in the thermal growing season (AT > 5 °C) in Poland, no statistically significant change in the average number of days with air frosts in the period 1971–2020 was found. On average, in Poland, in the years 1971–2020, a lengthening of the thermal growing season by 6.2 days over 10 years was identified. Earlier disappearance of the latest air frosts in spring was identified as 2 to 3 days over 10 years, and the later occurrence of air frosts in autumn as 1 to 4 days over 10 years. The share of *severe* (−4.1°C ÷ −6.0 °C) and *very severe* (<−6.0 °C) frosts in the total number of days with air frosts in Poland amounts to, on average, 5.8% in spring and 2.6% in autumn.

Keywords: negative minimum air temperature; spring; autumn; frost-free period; intensity; trend; frequency; dates; duration; variability; spatial; temporal

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1. Introduction

The characteristic manifestation of climate change observed worldwide, in Europe and in Poland, is an increase in air temperature [1]. Climate warming is followed by changes in the ranges of maximum and minimum values of air temperature, as well as the occurrence of characteristic days, e.g., hot, sweltering, cold, and frost. In the 20th century, the increase in minimum temperature reported in the northern hemisphere was higher than that of the maximum temperature [2,3]. However, in the last few decades, in Western and Central Europe, there has been approximately a two-fold increase in maximum temperature [4]. An increase in air temperature affects vegetation and has a significant effect on the dates of the beginning, end, and duration of the growing season. As a consequence, such changes in the climatic conditions also have an impact on agro-climatic resources which, in turn, determine the occurrence of particular development phases of plants [5,6].

Changes in the dates of the beginning and end of the growing season are particularly indicative of vegetation dynamics and long-term biological consequences of climate change [7,8]. The literature on the subject states that the increase in air temperature of 1 °C per year accelerates plant development by 2–5 days and if the acceleration takes place in spring, it can be even greater and amount to several days [9–12].

Yet another effect of climate warming is the observed shifting of climate zones to the north, which favours the cultivation of thermophilic plants such as grapevine, corn, soybean, and tobacco and also increases the risk of frost [13]. In the next few decades, the rate of migration of agro-climatic zones in Eastern Europe may be two times higher than that recorded in 1975–2016 [14]. Crops that have been genetically modified for the purpose of yield increase are often grown in non-native latitudes; therefore, phenological adaptation to the new conditions may last longer, making the plants more susceptible to frost damage [15].

The continent of Europe is distinguished by the greatest climate warming, which [16,17] presented in scenarios of the change, is most likely to be increasing [18,19]. The research carried out thus far provides clear evidence that the rise in air temperature across Europe and the neighbouring areas is characterized by temporal and spatial disparity [20,21]. Zveryaev and Gulev [22] demonstrated that in the summers and autumns of 1901–2000, the greatest warming was recorded in Western and Southern Europe; this is also true in winter in the south of the continent and in spring in Scandinavia and Northeastern Europe. As for Poland, the studies show that the greatest warming in the second half of the 20th century was recorded in the period of winter turning into spring and was most prominent in February and March.

In the temperate clime zone, there is a high variability of weather conditions, observed particularly in the transitional seasons (spring and autumn) when from day to day or even hour to hour, the air temperature may significantly change [23–25]. The reasons behind such large fluctuations in temperature observed in a short space of time may lie in the weather front system, solar radiation flow (clear day, cloudy day), temperature inversions, as well as local factors such as proximity to water reservoirs, mountains, or urban areas [25,26]. Large temperature fluctuations in spring and autumn lead to, among other things, the occurrence of frosts between the said seasons and damage or freezing of crops.

Frosts, being one of the unfavourable atmospheric phenomena, constantly pose a great threat to agriculture and horticulture in the temperate (transitional) climate zone in which Poland is located. Similarly, in North America and Europe, late spring frosts, in particular, cause damage to crops and trees and contribute to heavy economic losses in agriculture [27]. A great danger related to frosts occurs when plants are brought out of winter dormancy due to the earlier occurrence of spring and start the active growth stage, which is then followed by periods with lower temperatures (below 0 °C) [28–30]. Such periods are particularly dangerous during the most vulnerable stages of plant development, e.g., the occurrence of flower buds, flowering, or formation of fruit ovules [31–33]. With respect to field crops, the occurrence of frosts during the germination stage of, for example, spring barley or sugar beet results in losses in crop quality and yield [34–36]. In turn, with respect to winter rapeseed, frosts pose the greatest threat to inflorescence (falling of flower buds). They can cause stem damage (bending or longitudinal cracks in the stem), thus resulting in, for example, subsequent diseases or easier penetration by pathogens [37,38]. In agricultural and orchard cultivation, there are instances of frost damage of such magnitude that leads to the liquidation of the existing plantation and establishment of a new one; therefore, it has economic consequences. This was reported, for example, in 2011, 2012, and 2017 not only in Poland but also in Europe [27,31,39,40].

The literature on the subject distinguishes and discusses frosts, for example, due to their origin: advection, radiation, advection–radiation [41–44], occurrence: spring and autumn [13,45–47], intensity [34,39,47] or owing to the altitude of occurrence: ground frosts—5 cm above ground level [47–49] or air frosts—200 cm above ground level [50].

The frosts noted in Poland are mostly of advection–radiation character, owing to the inflow of cold arctic air masses [42–44], and occur most frequently in April and in the 1st and 2nd decade of May [28–30,51]. As a general rule, frosts usually occur as singular events, but there is a possibility of a consecutive series of 2 or more days [52]. In turn, given their intensity, the most common frosts are identified as slight (to −2 °C) or moderate (−2 to −4 °C), whereas severe (4–6 °C) and very severe (>6 °C) are recorded much less frequently [34,46,48]. The studies referred to herein consider and discuss frosts according to the adopted time period, termed the growing season, which most often covers the months of April to October (November). Due to the effects of climate change on agriculture, it is well known that with the positive trend in air temperature, there is a progressively earlier start of vegetation in spring which, consequently, results in time shifts of plant phenological phases [53–55]. In Western Europe, the start of vegetation occurs approximately 2 weeks earlier [56]. In Poland, the earlier occurrence of the growing season is estimated, depending on the adopted time period, as 4–6 days on average; however, it is more pronounced in the west rather than in the east of the country. Nevertheless, as presented by Koźmiński et al. [47], the number of days with ground frosts determined from the thermal threshold of 5 °C (thermal growing season) remained unchanged in the period 1971–2020. The earlier beginning of the growing season may also lead to an increased risk of frost damage when the trend of the beginning of the growing season is faster than the trend of the end of the frost period [57,58]. Therefore, it transpires that despite climate warming and lengthening of the growing season and the frost-free period [34,46,48,59], frosts may still be unfavourable for plants [60,61].

Climatic projections taking into consideration the growing season point to a greater risk of frosts after the beginning of the spring growth of plants in a warming climate [4,62,63]. There are also numerous studies [64,65] indicating that despite warmer winters, there is a lengthening of the period in which frosts may occur, regardless of the established lengthening of the frost-free period. Therefore, ongoing climate change does not decrease the risk connected with the occurrence of frosts, and the more pessimistic scenarios for climate change stipulate that the risk is to increase in thermal growing seasons.

The aim of the present paper is the assessment of the occurrence of frosts (200 cm above ground level) in Poland in the lengthening of the thermal growing season(AT > 5 °C) which favours earlier development of plants, thus causing an increased risk due to frost.

2. Materials and Methods

The study used time series measurement results of the minimum and average daily air temperature at the height of 200 cm above ground level from 52 meteorological stations of IMGW-PIB for the years 1971–2020 (Figure 1). A day with air frost was identified in instances when the recorded minimum air temperature was below 0 °C and mean air temperature in a 24-h period was above 0 °C. In the first stage of the present research, the dates marking the start, end, and duration of the thermal growing season (AT > 5 °C) were determined using the method by Gumiński (1948) [66]. The occurrence of frost was analysed only in the growing seasons as identified using the method. The dates of the last spring frost and the first autumn frost, the number of days and frequency of years with this phenomenon, and the duration of frost-free period were determined. If there is no frost in spring or autumn, the date of the last spring frost and the first autumn frost is taken as the beginning and end date of the growing season, respectively, to calculate the frost-free period.

The frequency of frost occurrence was characterised with respect to intensity: −0.1 °C to −2.0 °C (slight frost), from −2.1 °C to −4.0 °C (moderate), from −4.1 °C to −6.0 °C (severe) and below −6.0 °C (very severe). The values of regression coefficients were used to analyse the magnitude of changes of the analysed phenomenon over the 50-year period. Additionally, on the basis of standard deviation (S) from <−2 S to >2 S, the number of frost days occurring during the growing season was classified.

The mountainous areas with an altitude over 500 m above ground level were excluded from the analysis due to the predominant presence of grassland in such areas.

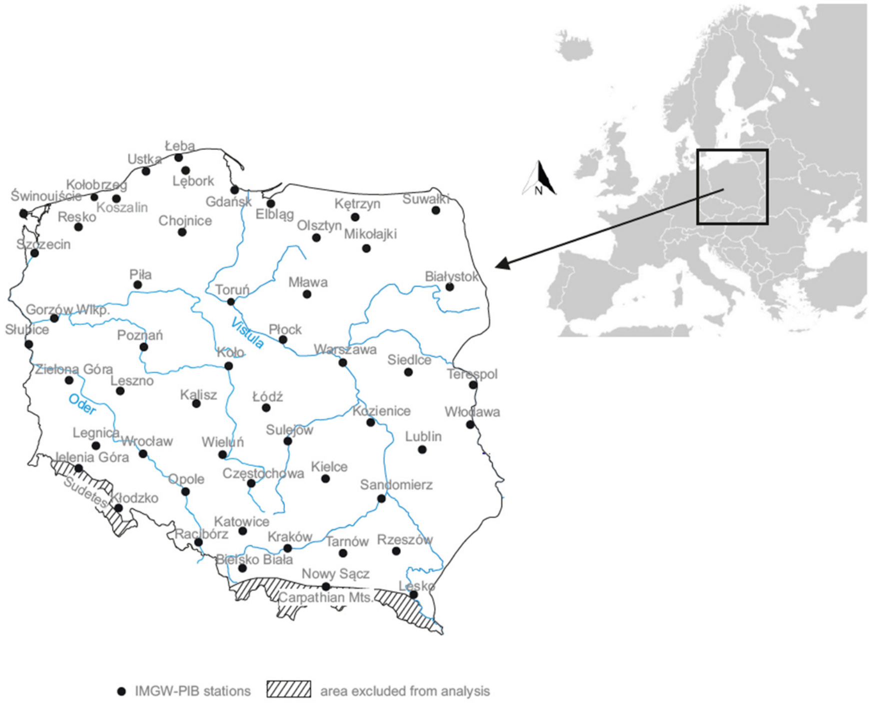

Figure 1. Distribution of IMGW-PIB meteorological stations in Poland.

3. Results and Discussion

The ongoing climate warming causes statistically significant, or highly statistically significant earlier occurrence of temperature >5 °C in spring as well as a delayed occurrence in autumn, which points to the lengthening of the growing season (Figure 2). On the basis of the available results presented in the literature on the subject, it was found that in the northern hemisphere in the years 1901–2009, the growing season was lengthened mainly due to earlier dates of occurrence in spring. In turn, using the measurement series for the period 1972–2020, Szyga Pluta et al. [67] observed that the most intense changes at the beginning of the growing season had been found in the last decades, particularly since the 1970s (e.g., −2.15 days/10 years—Kraków) and the 1980s (e.g., −3.1 days/10 years in Vienna). Similarly, the end of the growing season was lengthened with the highest rate since the 1980s in Kraków (5.12 days over 10 years) and since the 1970s in Vienna (5.27 days/10 years).

In the analysed multiannual period 1971–2020, a marked acceleration of the dates of the beginning of the growing season in spring was identified—from 1.5 days over 10 years in Nowy Sącz to 5.6 days in Ustka, and by, on average, 2.8 days countrywide. In autumn, progressively later dates of the end of the growing season are recorded—from 1.6 days in Elbląg to 4.5 days in Wrocław, the average for the whole country being 3.3 days. As a result, the duration of the growing season is found to lengthen, depending on the region of the country, by 3.3 days to 9.6 days and by 6.2 days over 10 years countrywide. The observed lengthening of the growing season is, to a slightly greater extent, determined by its later ending date (particularly in the last decades) than the earlier occurrence of the dates of the beginning [44,47,67,68]. The said variability as per exemplary stations and the whole country is presented in Figure 2.

The earliest beginning of the growing season is recorded in Lower Silesia—on average 16 March, and the latest in the northeast of Poland—after 1 April; in autumn, the earliest dates of the end, on average before 28 October, are recorded in the Suwałki Lake District, and the latest in Lower Silesia—after 13 November (Figure 3). In Poland, the progression of spring takes place from the southwest to the northeast of the country, and the progression of autumn from the east and northeast to the west and southwest [29,68,69].

Figure 2. The dates of the beginning, end, and duration of the growing season (AT > 5 °C) with the trend in Poland and in selected stations in the years 1971–2020.

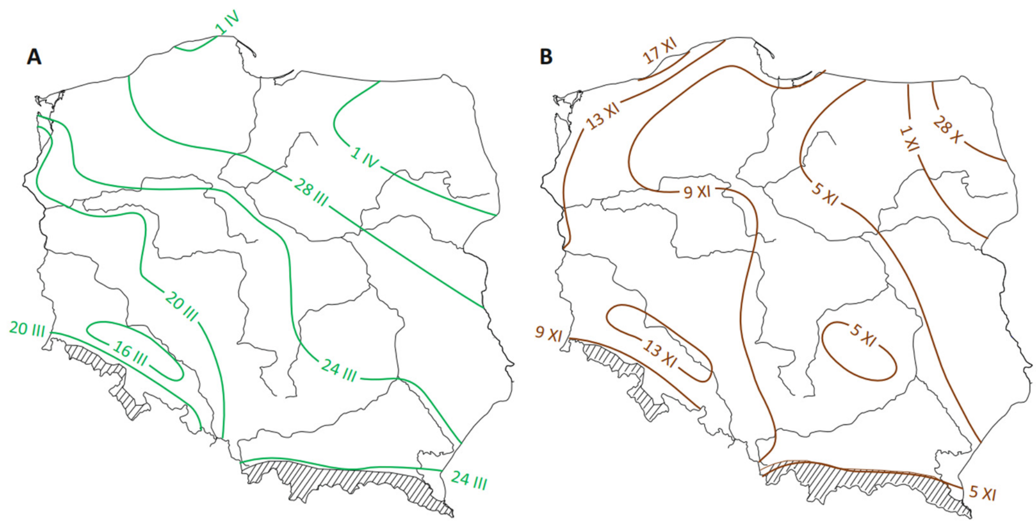

Figure 3. Average dates of the beginning (**A**) and end (**B**) of the growing season (AT > 5 °C) in Poland. Years: 1971–2020.

Due to climate warming, increased thermal resources in Poland, and the observed earlier start of the growing season, farmers and gardeners have the opportunity to expand the cultivation of thermophilic plants by increasing the amount of land dedicated to their growth [32,58,70–73]. However, in light of the above, there is a pressing need to determine whether frost still is a threat to plants.

The reliability of the assessment of frost risk in the conditions of the changing climate is determined by the adopted methodology. For example, with respect to the number of days with frost, the representation would be completely different depending if the analysis concerned the calendar or the thermal growing season. As is presented in Figure 4, the average number of days with air frosts in the whole country on a calendar basis (April–October) amounts to 10.3 and is characterised by a marked statistically significant negative trend (R^2 = 0.211). Such a static presentation would indicate a decreased risk of frost to plants. It is worth noting that the vast majority of studies on frosts in Poland present the issue on per calendar basis [34,45–49]. However, the number of days with frost as identified per thermal growing season is, on average, higher and amounts to 13.0 days and, more importantly, does not show statistically significant changes in the analysed multiannual period—Figure 4. A similar pattern identified for ground frost (5 cm above ground level) in the same set of stations and multiannual period was presented in the earlier study [47]. Similarly, their analysis of the data from the period 1961–2020 obtained from six stations located in two agricultural regions in Poland [13] found that despite earlier spring phenology owing to climate warming, the risk of plant damage due to frost remains unchanged. According to the authors of the present paper, the latter approach, i.e., the analysis of frost in the growing season, provides the actual assessment of the risk of frost to plants.

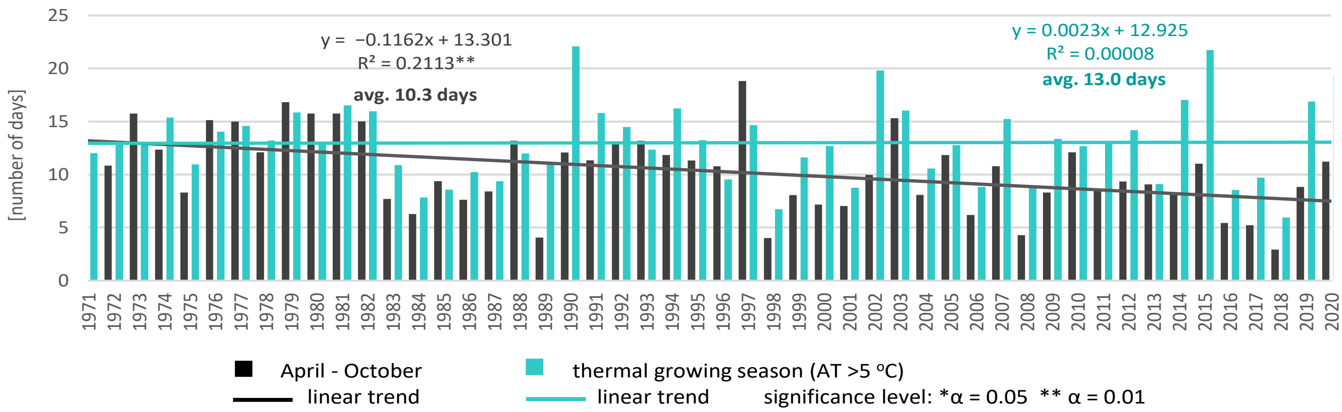

Figure 4. Average number of days with air frosts in Poland in the period April-October and in the thermal growing season (AT > 5 °C) with the trend in the years 1971–2020.

In spite of the unchanged number of days with an air frost in the 50-year-long period under analysis, the data presented in the figure below (Figure 5) indicate the earlier end of the last spring frost—on average, in Poland by 0.23 days per year, and later occurrence in autumn—by 0.20 day per year. However, in individual stations, there is a high variation of average dates of the last spring frosts and the first autumn frosts between the first (1971–1980) and the last (2011–2020) decade, as presented in Figure 6. For instance, in Kołobrzeg and in Koszalin, in the period 1971–1980, the last spring frosts ended, on average, on 24 April and 5 May, respectively; and in the last decade (2011–2020), much earlier—5 April and 17 April, respectively. In turn, in autumn in Łeba, for example, the occurrence of the first autumn frosts was markedly delayed—on average by as many as 24 days (12 October in the period 1971–1980; 5 November in 2011–2020).

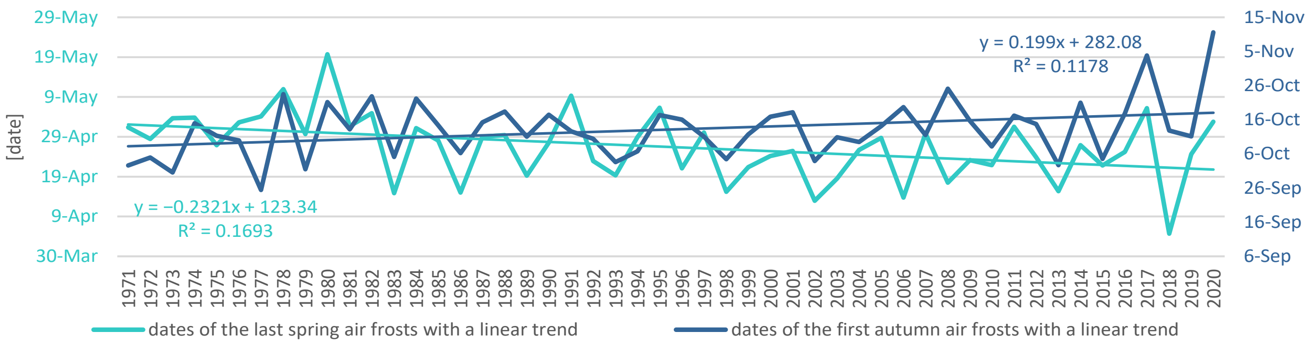

Figure 5. Average dates of the last spring air frosts and the first autumn air frosts in Poland in the growing season (AT > 5 °C) in the years: 1971–2020.

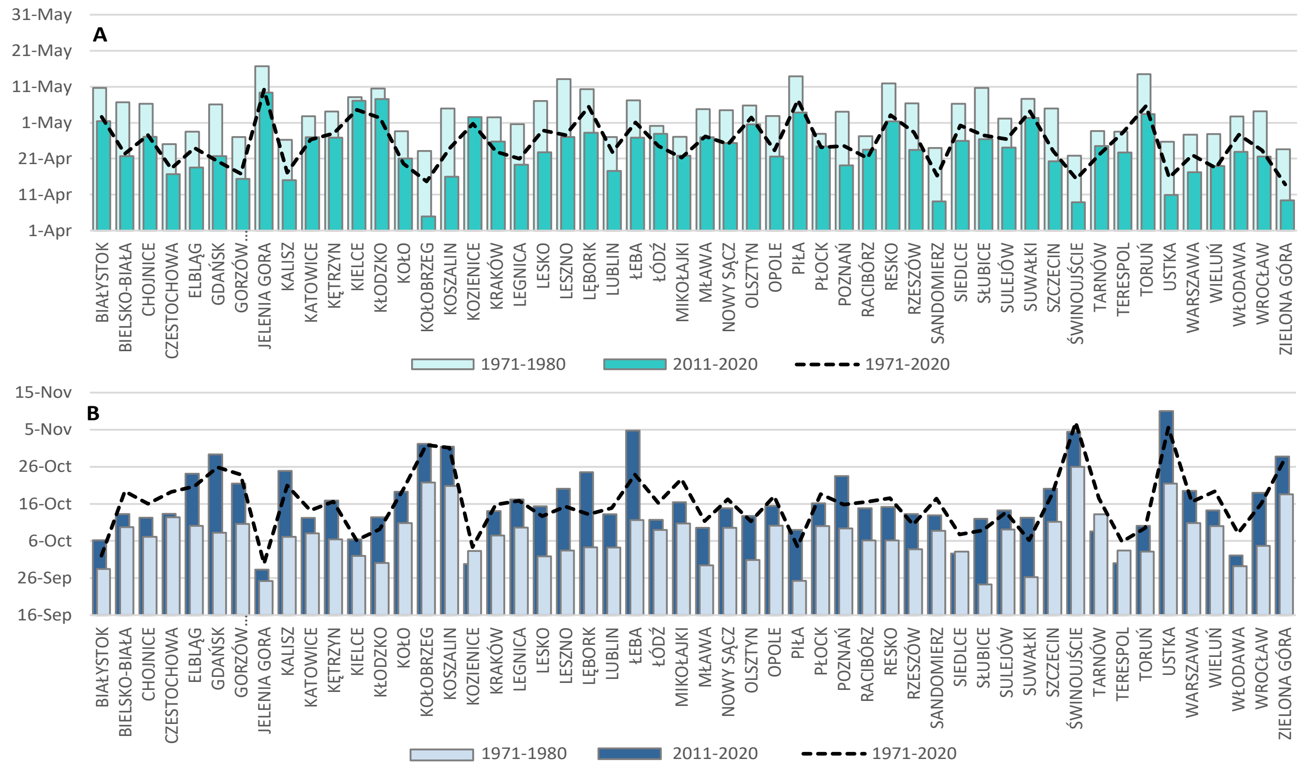

Figure 6. Average dates of the last spring air frosts (**A**) and the first autumn air frosts (**B**) in meteorological stations in Poland in the growing season (AT > 5 °C). Years 1971–2020.

In the period under analysis, i.e., 1971–2020, there were years in which the beginning of the thermal growing season was recorded as early as the end of January or the beginning of February (mainly in the western part of the country) when the first early spring frosts were recorded (Figure 7). Late spring frosts were still being recorded in the first and even the second decade of June. Similar results regarding the occurrence of the days of the last and first frosts were obtained by Dragańska et al. [34] and Graczyk [13]. Moreover, it is indicated that the occurrence of later spring frosts combined with warm winter may pose a risk to frost-resistant plants [73]. However, the results obtained in the course of the study show that by far, the most frost events were recorded in the second and first decade of April—the frequency of occurrence of years with frost was more than 70% in most stations. The first autumn frosts appeared sporadically as early as in the first decade of September; however, the prevalence was highest in the third and second decade of October (Figure 7). Comparable results were obtained by Tomczyk [46] and Dudek et al. [48] in their analyses of the frequency of occurrence of frosts in Poland.

months	January			February			March			April			May			June			July			August			September			October			November			December		
decades	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
BIAŁYSTOK								8	38	76	86	74	46	32	14	2									4	14	32	64	64	56	20	12				
BIELSKO-BIAŁA					4	4	10	38	62	70	68	42	22	12	4	2										2	2	20	48	72	42	16	10	6	2	2
CHOJNICE								10	44	66	84	60	30	14	4											2	12	24	46	50	20	6				
CZĘSTOCHOWA						2	8	26	56	64	60	34	16	2														16	42	64	26	12	2			
ELBLĄG					2		2	6	46	68	82	54	18	10	6												8	20	36	56	20	8			2	
GDAŃSK					2		4	14	34	40	52	36	20	10	4	2	2										4	12	22	44	28	14	8			
GORZÓW WIELKOPOLSKI					4	4	10	38	62	64	66	34	12	2														14	40	52	34	18	4	4	4	
JELENIA GORA						2	4	24	58	78	94	84	60	48	18	10									4	32	40	56	78	84	44	16	4	2		
KALISZ					2	2	6	26	60	62	66	38	14	4												2	2	14	50	64	32	22	8		2	
KATOWICE					2	2	14	36	72	82	80	50	28	18	6											2	12	22	52	86	52	20	4			
KĘTRZYN							2	12	34	64	86	56	30	14	8	2											14	30	42	56	12	6				
KIELCE							2	14	56	84	92	64	40	34	14	2										6	32	44	60	80	44	6				
KŁODZKO						2	4	24	52	82	90	70	44	24	12	4									4	10	14	34	68	78	36	16	4			
KOŁO					2		6	24	66	68	72	40	20	4	2												2	20	48	64	34	20	6	4	4	2
KOŁOBRZEG					2		8	14	38	44	56	26	8														2	6	24	34	36	30	14	6	2	
KOSZALIN					2		6	18	46	62	74	48	22	12	2	2											2	10	26	42	28	24	4		4	2
KOZIENICE					2		8	22	54	74	74	52	30	10	10		2								2	14	26	44	50	68	38	22	6			
KRAKÓW							12	34	72	76	74	48	26	14	2											2	6	26	48	84	54	20	2			
LEGNICA				4	6	10	14	46	74	72	76	48	16	4											2		4	22	52	70	56	36	14	6	2	
LESKO							4	18	56	78	82	52	34	16	10	2										4	18	30	48	72	34	14	4	2		
LESZNO					2	6	14	40	70	82	80	52	30	10	6	6									2	4	4	22	58	80	50	28	8	4	2	
LĘBORK					2		6	14	42	68	86	78	52	28	16	2										6	16	34	50	60	40	24	8	4	2	4
LUBLIN							4	16	52	66	68	48	22	8	4											2	12	26	54	68	30	8	2			
ŁEBA					2		4	8	32	50	72	72	38	20	4	4											4	16	40	50	38	20	8	4	4	2
ŁÓDŹ						2	6	22	64	78	82	50	32	8	4												4	32	56	72	36	16	4		2	
MIKOŁAJKI							2	12	26	52	80	44	18	4	2												2	18	30	46	14	6				
MŁAWA							2	14	44	74	86	50	34	12	8											8	16	32	62	68	24	6				
NOWY SĄCZ					2	4	12	42	72	70	72	56	28	14	2	2										2	8	28	42	72	54	22	12	6	2	2
OLSZTYN							2	12	40	72	88	68	42	22	10		2									10	20	36	50	64	22	10				
OPOLE					2	8	18	46	74	74	70	52	16	12	2											2	6	18	46	68	46	26	12	6	2	
PIŁA					2	2	6	24	58	78	90	74	48	30	18	8									8	12	24	42	66	78	44	12	4	4	2	
PŁOCK					2		6	20	58	72	72	48	26	8	4											2	4	24	52	68	32	14	4	2		
POZNAŃ					2	6	8	36	68	80	80	44	22	6	8										2	2	6	26	56	72	40	22	6	2	2	
RACIBÓRZ					2	6	16	42	60	72	68	44	20	8	4											4	6	22	52	66	44	20	6	4		
RESKO					2	2	8	14	48	72	82	60	36	22	10	4										4	6	24	48	52	26	14			2	
RZESZÓW						2	6	30	70	84	74	52	34	16	8	2										12	22	28	52	80	50	12	4			
SANDOMIERZ							6	28	60	58	58	38	14	4													2	22	56	76	36	16	2			
SIEDLCE							4	16	54	78	82	64	36	12	10		2									14	22	44	64	68	34	8				
SŁUBICE			2	2	2	10	14	44	72	82	84	58	38	10	8	4									6	8	20	40	56	72	60	34	6	8	2	2
SULEJÓW							4	18	58	82	82	58	28	14	6											2	8	32	62	86	42	10	2			
SUWAŁKI								4	16	48	90	72	48	28	12	2	2									12	30	50	48	44	10	8				
SZCZECIN			2	2	8	6	10	32	70	76	72	40	18	12	4											2	8	24	44	56	52	30	16	4	2	2
ŚWINOUJŚCIE					2	4	6	18	36	56	52	30	2	2															18	34	30	18	14	2	2	2
TARNÓW						2	14	40	72	76	70	50	16	10	4												10	24	42	80	42	18	10	6		
TERESPOL							4	14	56	78	78	52	30	10	10		2								2	12	28	50	64	76	34	8	2			
TORUŃ					2		6	24	60	88	88	68	42	32	18	2										10	16	34	60	74	38	18	4	4		
USTKA				2	4		4	14	28	40	54	34	8															6	18	34	28	24	14	4	2	2
WARSZAWA					2	2	6	24	58	78	74	44	22	8	2												10	30	58	72	36	14	4			
WIELUŃ							6	22	58	76	66	38	18	6	2												4	22	46	66	26	12	4			
WŁODAWA							4	14	54	82	76	52	34	16	6		2									10	22	40	64	74	32	6				
WROCŁAW				4	8	12	20	46	80	78	72	56	20	14	2										2	4	2	26	52	68	52	36	16	6	2	
ZIELONA GÓRA					2	4	8	26	54	58	52	30	8	2														6	26	48	26	10	4	2	2	

Frequency: 0 10 20 30 40 50 60 70 80 90 100 % (spring frosts); 0 10 20 30 40 50 60 70 80 90 100 % (autumn frosts)

Figure 7. Frequency of years with spring air frosts and autumn air frosts recorded in meteorological stations in Poland in the growing season (AT > 5 °C) per decade. Years 1971–2020.

In Poland, with respect to occurrence, frosts show not only high temporal but also spatial variability. The earliest end of spring frosts at an altitude of 200 cm is observed recorded in the western coastal area—on average before 20 April and the lastest end after 5 May in the northeast part of the country and in the Sudetic Foreland (Figure 8a). There is a clear spatial variability in terms of dates of occurrence of frost in the coastal zone and in the east of Poland, i.e., climatically contrasting areas of the country [32]. In the predominant area of Poland, the spring frosts described here end, on average, after 30 days after the average dates of the beginning of the growing season (Figures 3 and 8a). However, attention must be paid to the fact that the last spring frosts were recorded on the coast, e.g., in Świnoujście till 12 May, in Lower Silesia, in Legnica till 17 May, and in the Suwałki Lake District as late as until 11 June.

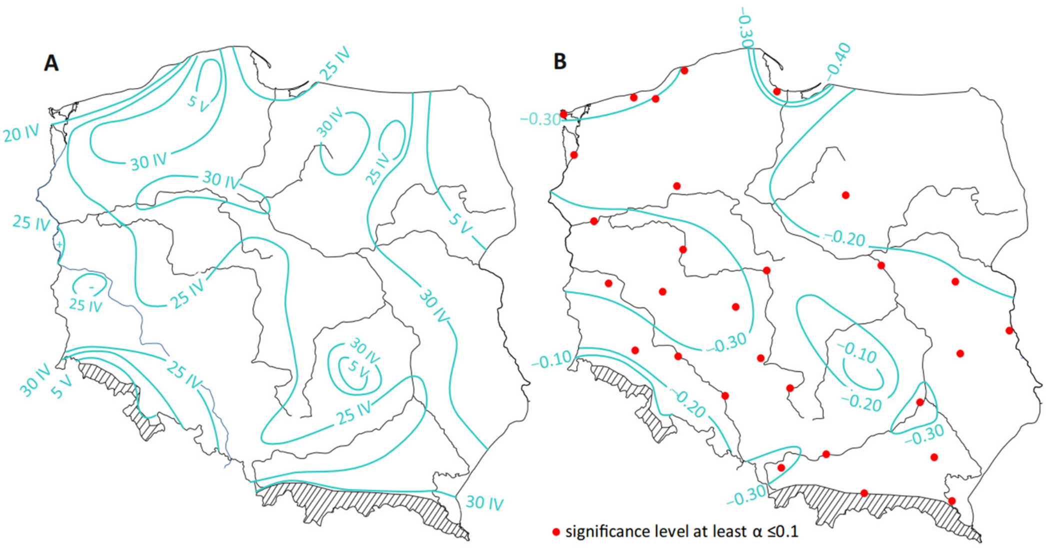

Figure 8. Mean of the dates of the last spring air frosts (**A**) and the values of regression coefficients of the last spring air frosts (**B**) in Poland. Years 1971–2020.

Additional information on the phenomenon under analysis is provided by the values of regression coefficients concerning the dates of the last spring frosts, which in most stations proved to be statistically significant or highly statistically significant. As can be seen in Figure 8b, the smallest changes (−0.10 to −0.20 days in a year) were recorded in the Sudetes and in the northwest of Poland, slightly larger (−0.21 to −0.30 days in a year) in most of the country. The highest values of the said coefficient below −3.0 days in a year were found on the coast and in the central basins of the Odra and Warta Rivers.

First autumn frosts occur the earliest, on average before 5 October, in the northeast of Poland and in the Sudetic Foreland, and the latest, on average after 25 October, in the coastal zone. However, in the predominant area of the country, autumn frosts occur in the second decade of October (Figure 9a). In autumn, the earliest dates of occurrence of frosts in the whole multiannual period were recorded in the Odra River basin, e.g., Wrocław 8 September and the latest date was found on the coast, Kołobrzeg 28 September, due to the warming effect of the waters of the Baltic Sea [74,75]. The values of the regression coefficient for days of the first autumn frosts are from 0.20 days in a year in the southeast of Poland to 0.30 in the north of the country and in the central basin of the Warta River (Figure 9b).

As shown in Figure 10a, the average number of days with spring frosts during the growing season introduces high spatial variability throughout the country—approx. 4 days in the western part of the coast, 8 days in the central area of Poland, and exceeding 10 days in the upper basins of the Narew and Biebrza Rivers, the Łeba and Reda Rivers ice-marginal valley, in Lower Silesia, in the area of the Świętokrzyskie Mountains, in the Carpathian Foothills and the Sudetic Foreland. In autumn, spatial variability of the average number of days with frosts in the growing season is markedly lower—approx. 4 to 6 days (Figure 10b).

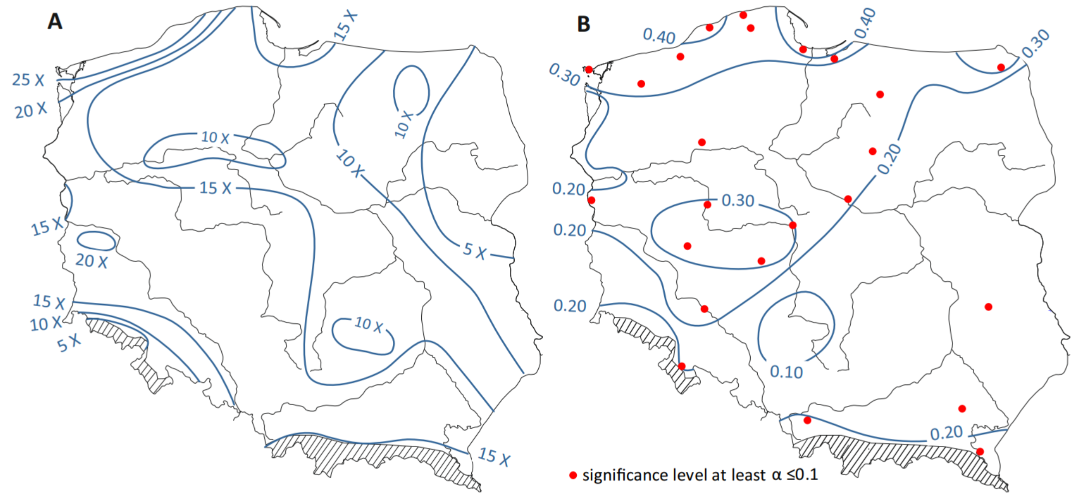

Figure 9. Mean of the dates of the first autumn air frosts (**A**) and the values of regression coefficients of the first autumn air frosts (**B**) in Poland. Years 1971–2020.

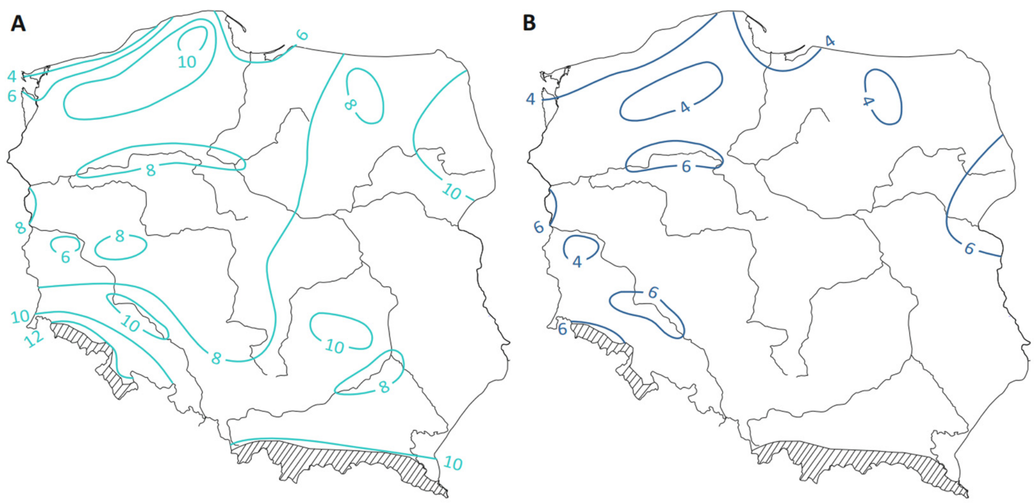

Figure 10. Average number of days with air frosts in spring (**A**) and autumn (**B**) during the growing season (AT > 5 °C) in Poland. Years 1971–2020.

Frosts in spring, autumn, and the whole growing season were characterised for individual years in selected stations (Figure 11). In spring, the followings years are marked in terms of the increased number of days with frosts (more than 1 and more than 2 S): 1974, 1981, 1990, and 2020, whereas with respect to decreased number of days with frost (below 1 S): 1986 and 1987, 2006, 2010 and 2013. The recorded a large number of days with spring frost generally does not translate into their increased occurrence in autumn in the same year. The large number of days with frost in autumn was recorded in 1979, 1994, 2003, and 2015 and the small in 1974, 1989, 1998, 2016–2018, as well as in 2020. Figure 11 also shows high variability and irregularity of frost occurrence in Poland from one year to another.

In Poland, generally, *slight* frosts (<0.0° ÷ −2.0 °C) are recorded, and the frequency of days of their occurrence in most stations in spring is from approx. 32 to 54% in autumn from approx. 20 to 35% of all days with f rost in the thermal growing season. A markedly lower frequency of days with *moderate* frost (−2.1 °C ÷ −4.0 °C), from approx. 9 to 23% in spring and approx. 3 to 13% in autumn. The share of *severe* frost (−4.1 °C ÷ −6.0 °C) and *very severe* frosts (<−6 °C) in the total number of days with frost in spring is below 10%, and in autumn—below 5% (Figure 12).

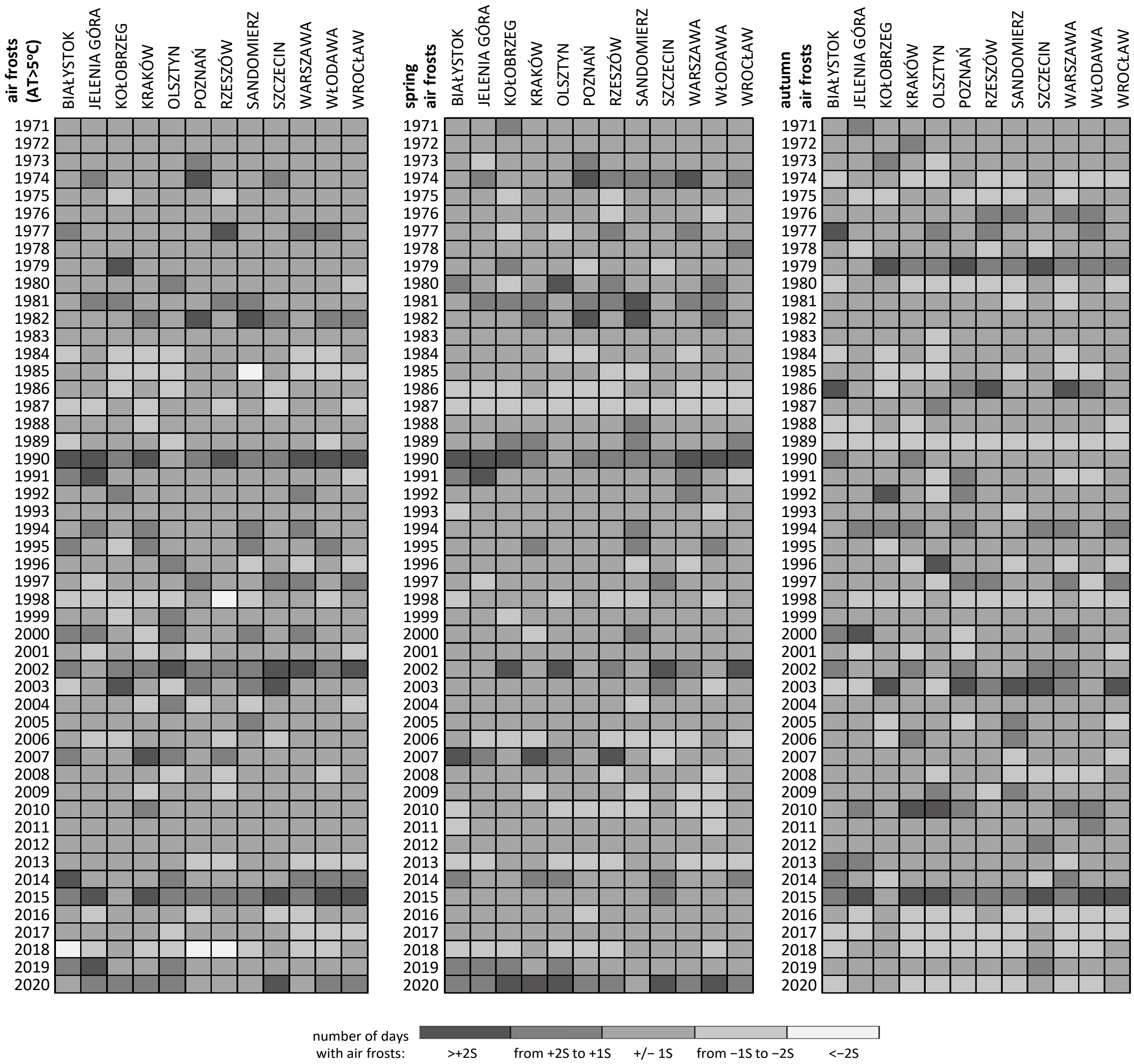

Figure 11. Classification (according to standard deviation) of the number of days with frost in subsequent years of the period 1971–2020 in selected stations.

The analysis of the occurrence of frost of various intensities in meteorological stations (Wrocław, Białystok) in subsequent years of the period 1971–2020 shows high variability from one year to another, however without a significant trend for the whole period (Figure 13). It must be emphasized that sporadic occurrence of *very severe* frost was recorded mainly in early spring.

In the growing season, most *slight* frosts are recorded in the area of water reservoirs (the Baltic Sea, lakes) and in the upper basin of the Warta River, whereas *slight* frosts are recorded in the aforementioned locations with a lower frequency, as compared with other areas of Poland. *Severe* and *very severe* frosts are characterised by lower spatial variability in comparison with *slight* and *moderate* frosts since their occurrence is noted in the predominant area of the country. Variability in terms of the frequency of occurrence and intensity of frosts is also indicated by Wieteska [36]. In turn, the study by Więcław [76] shows that frosts in Poland occur mainly in the arctic air, followed by continental polar air and polar maritime cold air.

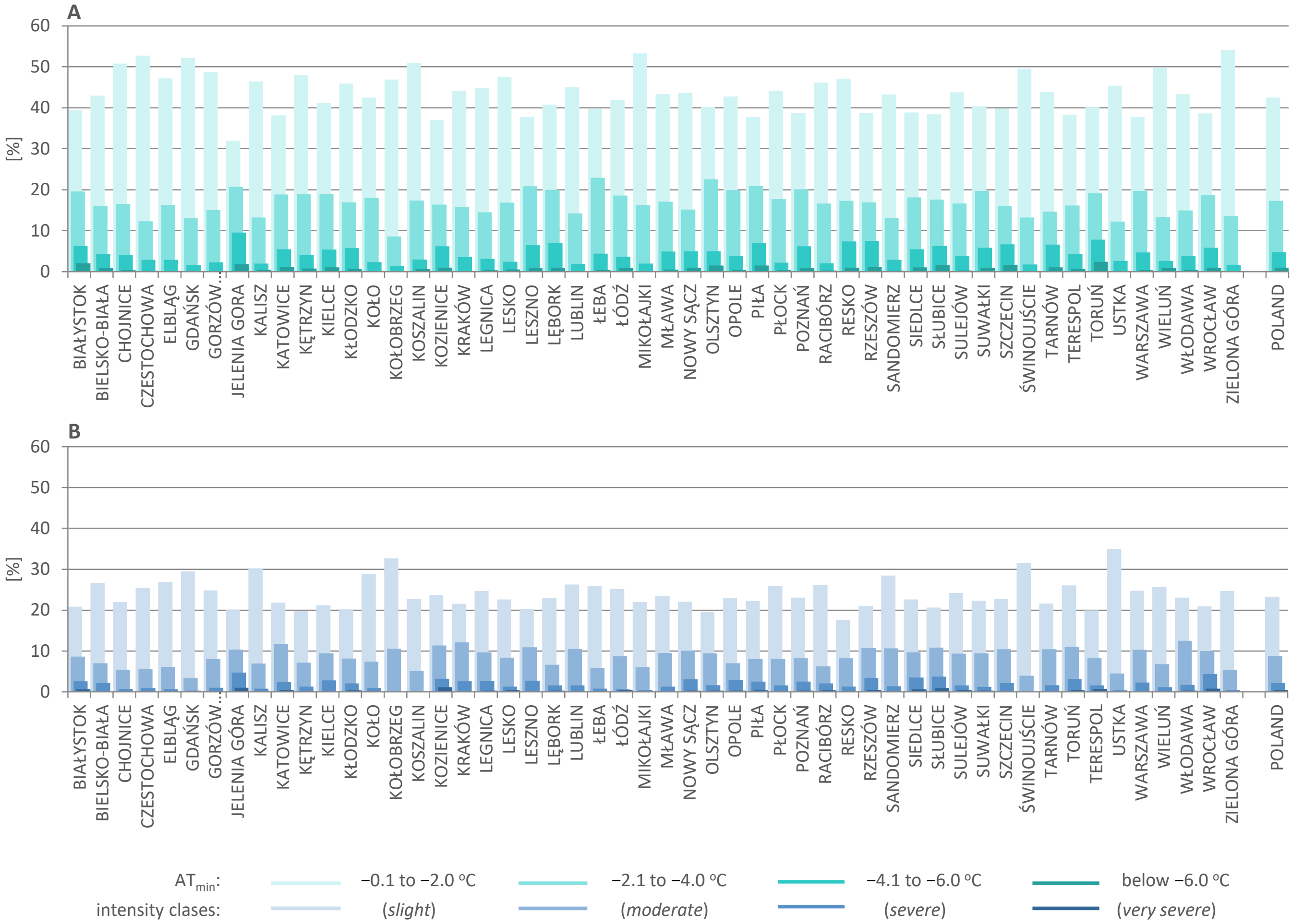

Figure 12. Frequency of air frosts in spring (**A**) and autumn (**B**) per intensity classes recorded in meteorological stations in Poland. Years 1971–2020.

The last characteristic used for the assessment of frost is the frost-free period (understood as the number of days between the last spring frost and the first autumn frost), which in the northeast of Poland is less than 155 days; in central Poland, approx. 175 days; and in the west coast zone, more than 195 days (Figure 14a). On average, on the scale of the whole country, the air frost-free period is 172 days, which is by 31 days longer in comparison with the ground frost-free period [47]. Consequently, spatial variability of the duration of the frost-free period in Poland amounts to, on average, approx. 40 days. According to Bielec-Bąkowska et al. [43], from 1951–2006, the frost-free period lasted approximately 166 days, and the greatest effect on the increase in the duration of the frost-free period in Poland is attributed to a marked increase in air temperature starting from the 1990s.

Additional information on the phenomenon under analysis is provided by the values of regression coefficients concerning the frost-free period, which in most stations proved to be statistically significant or highly statistically significant. The highest values of regression coefficients (>0.6 days in a year), indicating the lengthening of the frost-free period, were recorded in the areas adjacent to the Gdańsk Bay, the western part of the coast, and the midwestern area of the country. In turn, the lowest increase in the said period (<0.40 day in a year, locally even <0.30 day) is found for the Masurian Lake District and in the upper basins of the Wisła and Odra Rivers (Figure 14b). The lengthening of the air frost-free period presented above takes place at a slightly slower pace than that of ground frost [7]. As reported by Bielec-Bąkowska et al. [43], such great spatial and temporal variability of the occurrence of the frost-free period in Poland may be explained by the location of the station, which, in turn, is connected with the influence of the Baltic Sea, mountains or its location in the continental climate impact zone.

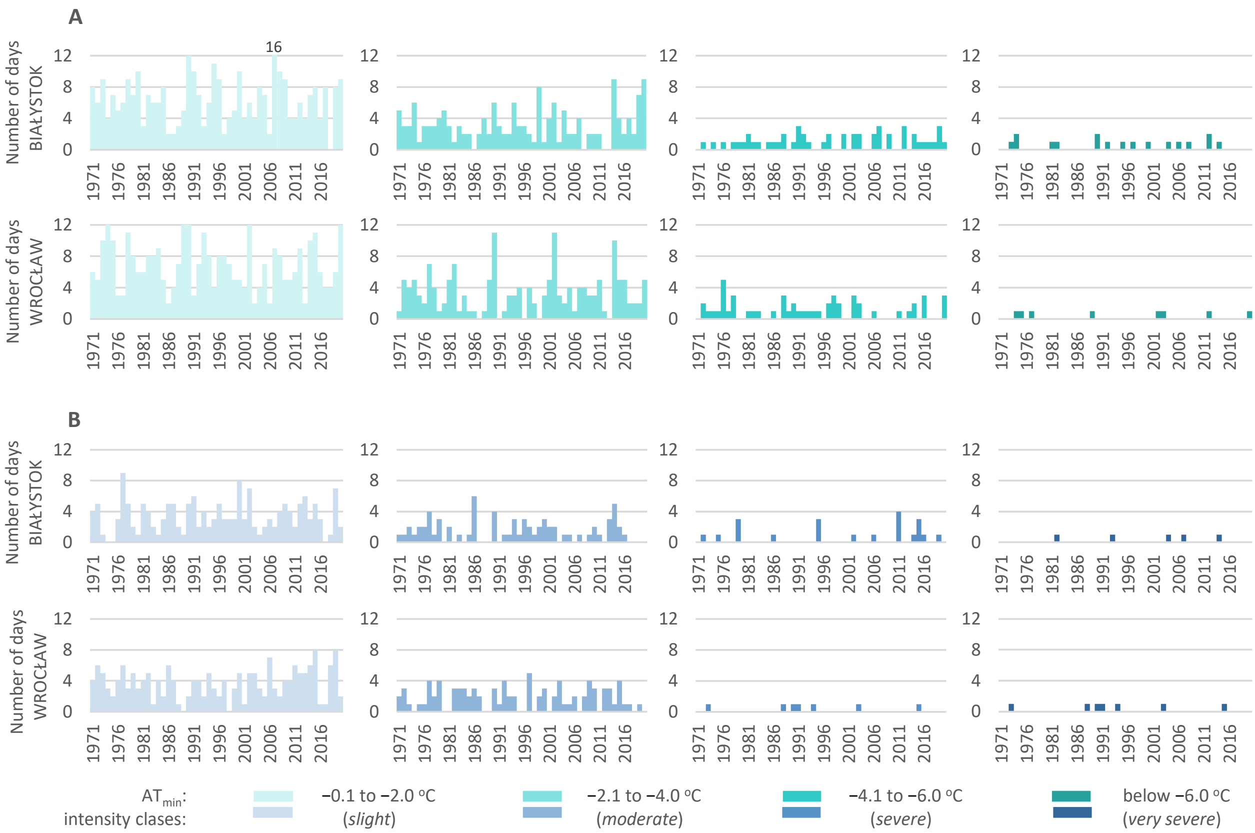

Figure 13. The number of days with air frosts by intensity classes in spring (**A**) and autumn (**B**) in Białystok and Wrocław. Years 1971–2020.

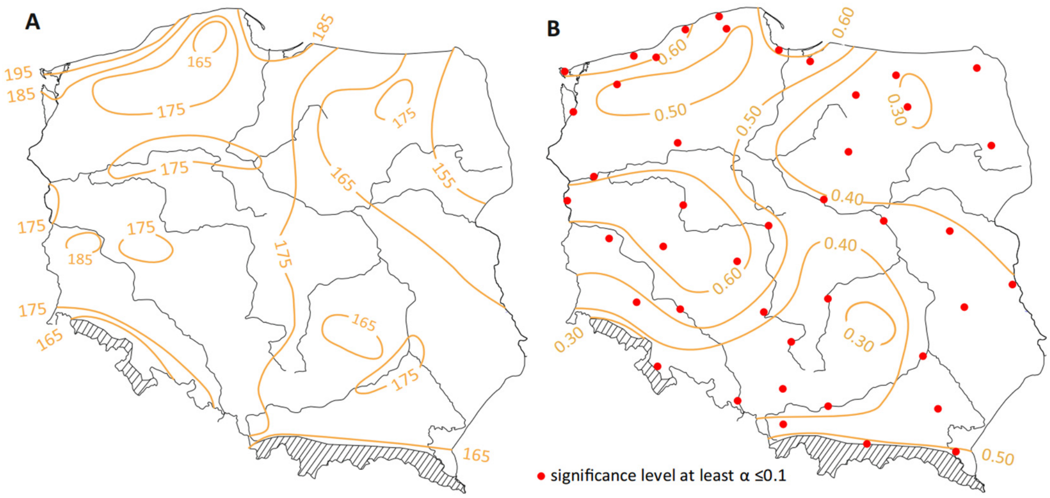

Figure 14. Average duration of the air frost-free period per day (**A**) and the values of regression coefficients of the air frost-free period (**B**) in Poland. Years 1971–2020.

4. Conclusions

The presented study concerns the analysis of air frosts in distinct temporal frameworks related to the thermal growing season (AT > 5 °C).

Due to climate warming, the multiannual period from 1971–2020 is marked by an increasingly earlier occurrence of air temperature >5 °C in spring on average in Poland by

2.9 days over 10 years to increasingly later dates of end in autumn, on average by 3.3 days, which, consequently, results in the lengthening of the thermal growing season—on average, in Poland, by 6.2 days over 10 years.

Spatial variability of the dates of the beginning of the growing season in Poland is, approx., 2 weeks—on average, the earliest beginning, i.e., before 16 March, is recorded in Lower Silesia, and the latest, i.e., after 1 April in the northeast of Poland. Greater spatial variability of the dates of the end of the growing season, however, with the opposite direction of change, occurs in autumn, before 28 October in the area of Suwałki and after 17 November in the area of Wrocław.

Spatial variability of the average dates of the last spring frosts at an altitude of 200 cm above ground level in Poland amounts to more than 2 weeks—on average, the earliest end i.e. before 20 April is recorded on the coast, and the latest end, i.e., after 5 May in the Narew River basin. In turn, the average dates of the occurrence of the first autumn frosts fall in the first decade of October in the northeast of Poland, whereas along the coast, due to the warming effect of the Baltic Sea, in the last pentad of the said month. In the analysed 50-year-long period, earlier end of the last spring air frosts, from approx. 2 to 3 days over 10 years, and later occurrence in autumn, from 1 to 4 days over 10 years, are recorded.

In the whole area of Poland, spring frosts are recorded in the second decade of April, followed by the first decade of April and the third decade of March. In autumn, the increased frequency of frosts is recorded in the third decade of October, followed by the second decade of the said month.

In the thermal growing season (AT >5 °C), the average number of days with spring frost varies from approx. 4 to 10, and is almost two times higher than that in autumn. Compared to the rest of the country, an average number of days with frost in Lower Silesia results from the earlier beginning of the thermal growing season.

In the thermal growing season (AT >5 °C) in Poland, there was no statistically significant change in the average number of days with air frosts in the period 1971–2020.

In the analysed years in Poland, high variability of the number of days with frost from one year to another was found, and the years with very high ($S > 1$) as well as low ($S < -1$) intensity of frost was rarely recorded in spring and in autumn, from four to seven events in the 50-year long period under analysis.

The share of *severe* frosts (−4.1 °C ÷ −6.0 °C) and *very severe* frosts (<−6.0 °C) in the total number of days with frosts in Poland, on average, amounts to 5.8% in spring and 2.6% in autumn.

Moving from the northeast to the southwest of Poland, there is an increase in the duration of the air frost-free period, on average, from approx. 155 to approx. 175, and in the coastal zone, even more than 195 days. In the analysed 50-year-long period (1971–2020), the duration of the frost-free period was longer by approx. 20 days in the Masurian Lake District to approx. 30 days in the midwestern part of Poland and in the coastal zone, which increases the possibility of thermophilic plant cultivation.

The ongoing climate warming is increasing thermal resources across the territory of Poland, and the earlier beginning of the growing season makes it possible for farmers and gardeners to increase the thermophilic plant cultivation area.

In conclusion, despite the earlier beginning of the growing season and earlier plant phenology due to climate warming, the obtained results suggest that the risk of frost damage to plants remains almost unchanged.

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