QUAESTIONES GEOGRAPHICAE 42(1) • 2023

PATTERNS IN THE MULTIANNUAL COURSE OF GROWING SEASON IN CENTRAL EUROPE SINCE THE END OF THE 19TH CENTURY

Katarzyna Szyga-Pluta [1], Arkadiusz M. Tomczyk [1], Katarzyna Piotrowicz [2], Ewa Bednorz [1]

[1] Department of Meteorology and Climatology, Adam Mickiewicz University, Poznań, Poland
[2] Department of Climatology, Jagiellonian University, Kraków, Poland

Manuscript received: March 18, 2022
Revised version: October 31, 2022

Szyga-Pluta K., Tomczyk A.M., Piotrowicz K., Bednorz E., 2023. Patterns in the multiannual course of growing season in Central Europe since the end of the 19th century. *Quaestiones Geographicae* 42(1), Bogucki Wydawnictwo Naukowe, Poznań, pp. 59–74. 4 figs, 3 tables.

Abstract: The research identified patterns in the multiannual course of start and end dates, and length of growing season (GS) in Central Europe since the end of the 19th century in selected cities of Central Europe in the period 1893–2020. GS start in the analysed stations was characterised by high year-to-year variability, particularly in those located more southwards, i.e. in Prague and Vienna. A smaller variability occurred in GS end dates. The GS was subject to prolongation, although these changes in particular cities were uneven and had different causes. In Toruń and Potsdam, its increase was caused by a greater shift of the end date, and in the remaining stations, it was determined by its earlier start date. Two subperiods were distinguished that differ in terms of intensity of changes of the start and end dates, as well as the length of the GS. The intensification was observed recently.

Keywords: growing season, air temperature, multiannual series, Central Europe

Corresponding author: Katarzyna Szyga-Pluta; pluta@amu.edu.pl

Introduction

Next to atmospheric precipitation, air temperature is one of the primary factors determining vegetation development, including growing season start (GSS), end (GSE) and length (GSL). Research on the changes and variability of the growing season (GS) correspond with issues related to climate changes and adaptation to such changes (Chen et al. 2000). GS start and end are considered to be among the best indicators of the vegetation dynamics and long-term biological effects of climate change (Peng et al. 2017, Duarte et al. 2018, Cui, Shi 2021).

In the majority of publications, based on three types of data (phenological, satellite, and climatological), the authors evidenced a considerable increase in GSL in different regions around the globe over the recent decades, caused by its earlier start date and later end date (Chmielewski, Rötzer 2002, Walther, Linderholm 2006, Christidis et al. 2007, Barichivich et al. 2013, Liu et al. 2016, Park et al. 2016, Cui et al. 2017, Koźmiński et al. 2021) A review of results of other studies on

https://doi.org/10.14746/quageo-2023-0005
ISSN 2082-2103, eISSN 2081-6383

GSL until the end of the 20th or first years of the 21st century was performed and published by Linderholm (2006).

According to Xia et al. (2013), it is difficult to compare results globally regarding GSL variability in the last century due to limited access to multiannual daily measurement series. Therefore, in their paper (Xia et al. 2013), the authors applied a linear correlation between the GS start and end date and mean monthly temperature in April and October in the Northern Hemisphere. They determined that in the period 1901–2009, GSL averaged for the study area increased, primarily due to its earlier start. Trends of GSL changes, however, were lower than those resulting from analyses based on data from the second half of the 20th century (Xia et al. 2013). Also, according to Dong et al. (2013), GSS and GSE fluctuations are closely correlated with the mean monthly temperature (Tmean) of April and October, respectively, and GSL was stronger correlated with minimum temperature (Tmin) in spring (March–April) and autumn (September–October). In the GS in Poland in the period 1966–2015, greater changes occurred in thermal than precipitation conditions (Tomczyk, Szyga-Pluta 2019).

The GS and its multiannual changes are usually associated with a potential change in the terms of planting, development, and maturing of plants and harvest yields. GSL, however, does not only affect the vegetation, including plant yield but also the hydrological cycle: snow melt, surface runoff, evapotranspiration, and soil moisture, and translates into an increase (in the case of longer GSL) or decrease (in the case of shorter GSL) in water use (Peterson et al. 2002, Groisman et al. 2004, Backlund et al. 2008, Christiansen et al. 2011). Earlier snow melt negatively affects the shift of maximum flow rate in some rivers (Barnett et al. 2005), and tourism in skiing areas (Beniston 2003, Nicholls 2005).

According to research by Ryan and Archer (2008) and Fagre et al. (2009) in the USA, the observed changes in GSL will also contribute to changes in plant species in forests. Prolongation of GSL also affects life cycles, particularly those of migratory birds, and insect invasions (Cotton 2003, Logan et al. 2003, Janetos et al. 2008). For example, GS prolongation in Germany (4.2 days per decade) and Slovenia (1.0 days per decade) contributed to the prolongation of phenological seasons of oak, birch, and beech, but simultaneously to the reduction of the season of chestnut (−12 days per decade) caused by attacks of pests (Menzel et al. 2008). Many plant and animal species expanded their ranges towards the poles over the last century (Parmesan, Yohe 2003, Haggerty, Mazer 2008). It should be remembered, however, that GS prolongation can cause competitive relations between plants in different ecosystems (Kolářová et al. 2014). Unfavourable effects of GS prolongation are also observed in the reduction of planning of certain crops, among others rice (Peng et al. 2004).

The analysis of the GS is currently based on three types of data: meteorological (air temperature values), phenological observations, and satellite data (Normalized Difference Vegetation Index – NDVI) (Cui, Shi 2021). Results of comparative research from these three types of data conducted by Cui and Shi (2021) in northern China show that the dates of GSS and GSE determined based on air temperature are earlier than those from phenological observations, and those determined from the NDVI index proved the latest. Unfortunately, each of these methods has its advantages and drawbacks. Multiannual (>100 years) GS variability can be determined only based on the former type of data, namely air temperature measurements or alternatively, phenological observations, but these have been and are conducted only locally due to their time and labour-consuming character (Studer et al. 2007). Satellite data are limited only to the period of the last several decades. According to Walther and Linderholm (2006), the spatial and temporal assessment of changes in the GS can only employ measurements of air temperature, because it is considered the primary factor limiting vegetation growth. Moreover, access to air temperature measurements is much simpler, and even measurement series dating back to the 19th or 18th century can be used.

There is no commonly adopted method to thermally define the GS. Therefore, it is difficult to compare results published by different authors. In research on the GS where authors have used meteorological data, i.e. about air temperature, it was usually defined employing constant thermal thresholds. The difficulty in its calculation lies in the determination of temperature thresholds that should be universally applicable at the GSS and GSE (Kexin et al. 2021). For average and higher latitudes, the threshold value commonly adopted as the start of the GS is 5°C, because it is considered the lowest temperature for the growth of plants (Frich et al. 2002, Barichivich et al. 2013, Cui et al. 2018).

The threshold of 5°C was applied among others in research by Jones and Briff (1995), Carter (1998), and Frich et al. (2002), whereas the research considered mean daily or minimum air temperature (Menzel et al. 2003). For example, Frich et al. (2002) defined GSL as a period at the start of which mean daily temperature was above 5°C for >5 subsequent days, and at the end of which it is maintained below 5°C for >5 days. Linderholm et al. (2008) modified this definition so that GSS occurs on the last day of the first 6-day period with a mean daily temperature above 5°C after the last frost, and GSE is the first day of a 10-day period with a temperature below 5°C. Bootsma (1994) defined the analysed season as a period between a 5-day weighted average temperature maintained above 5.5°C and falling below 5.5°C, respectively, and Jones et al. (2002) – start/end as the first/last 5-day period with a temperature above 5°C occurring after/before the last/first frost of the winter season. Unfortunately, differences in the way of determination of specific dates of temperature transition through a given temperature threshold still exist (Walther, Linderholm 2006, Qian et al. 2009). Nonetheless, Xia et al. (2015) suggest that a relevant combination of mean monthly air temperature values can be used as an approximation of the season start.

Few studies analyse the GS based on larger than 100-year air temperature measurement series. Meteorological stations with such long measurement series are located in large cities. Therefore, they do not represent areas under agricultural use or natural vegetation cover. Research by Jones et al. (2002) used a 200–250-year-long series of air temperature measurements in Europe from four locations: Central England, Stockholm, Uppsala, and St. Petersburg. According to the authors, the temperature in the GS increased in Fennoscandia before 1860, and in Central Europe and central England, GSs at the end of the 20th century were approximate to those occurred before 1860. More than 100-year-long data series was also applied by Walther and Linderholm (2006). The authors analysed the Greater Baltic Area and determined that the greatest fluctuations of trends of changes in the GS occurred in Denmark (the differences exceeded half a month), and in Stockholm (Sweden) only small differences were observed. Carter (1998) used measurements during the period 1890–1995 from 10 stations in the Nordic region (Finland, Sweden, Norway, and Iceland). He determined that GS in all stations increased, but the rate of changes, particularly after 1960, was somewhat different, especially in Iceland. The obtained results presented by different authors largely depend on the applied index characterising the GS and a given area, although according to Walther and Linderholm (2006), the criterion of GS determination defined by Jones et al. (2002) (start) and Carter (1998) (end) proves effective in northern Europe.

The objective of this paper is to determine patterns in the multiannual course of dates of the start (GSS), end (GSE), and length (GSL) of the thermal GS in selected cities of Central Europe since the end of the 19th century. Particular attention was paid to the tendency of changes in selected parameters of the analysed season.

Materials and methods

The study was based on values of mean monthly air temperature in six stations in Central Europe: Kraków, Potsdam, Poznań, Prague, Toruń, and Vienna (Fig. 1). The analysis covered the longest available period, that is, 1893–2020, and even for all stations. Data from Potsdam and Prague were obtained from national meteorological services, namely Germany's National Meteorological Service and Czech Hydrometeorological Institute, respectively. In the case of the stations in Poznań and Toruń, it was based on archive data provided in publications by Kolendowicz et al. (2019) and Pospieszyńska and Przybylak (2019). Data from recent years were obtained from the archive of the Institute of Meteorology and Water Management – National Research Institute. Data from Kraków were obtained from the research station of the Department of Climatology of the Institute of Geography and Spatial Management of Jagiellonian University. Data from Vienna were obtained from publicly available bases of

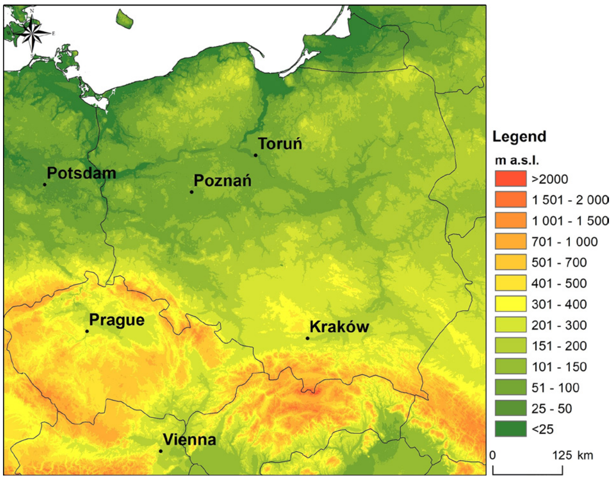

Fig. 1. Location of the stations.

the historical instrumental climatological surface time series of the Greater Alpine Region (HISTALP). The used data were verified in terms of quality and uniformity, as were relevantly explained in the source materials of such data.

The aforementioned data provided the basis to first determine the dates of the start and end of the GS, defined as a period with mean daily air temperature of >5°C. The above definition has been previously adopted in numerous studies (Carter 1998, Skaugen and Tveito 2004, Linderholm et al. 2008). The determination of GSS and GSE dates employed mathematical formulas proposed by Gumiński (1948). The method was based on the following assumptions: mean monthly temperature occurs on the 15th day of the month, each month has 30 days, and month-to-month changes in temperature occur evenly. The following formulas were applied:

$$x = 30\ [(tp-t_1)/(t_2-t_1)] \text{ for GSS,}$$

$$x = 30\ [(t_1-tp)/(t_1-t_2)] \text{ for GSE,}$$

where:
- tp – threshold temperature (5°C),
- t_1 – mean temperature in the month preceding the threshold temperature,
- t_2 – mean temperature in the month following the threshold temperature,
- x – number of days separating the day with the threshold temperature from the 15th day of the preceding month.

The number of days calculated based on the above formulas is added to the 15th day of the month preceding the threshold temperature. If the resulting number is >15, the addition should consider the actual number of days in a given month. The obtained data is the GS start or end. The described method is commonly adopted in the determination of the GS as well as the other thermal seasons of the year (e.g. Skowera, Kopeć 2008, Szyga-Pluta 2011, Kępińska-Kasprzak, Mager 2015, Tomczyk, Szyga-Pluta 2019). Bartoszek and Siłuch (2015) evidenced considerable conformity of average GSS terms determined using the Gumiński method (1948) and satellite teledetection in the decade 2001–2010.

The next stage involved the calculation of GSL in particular years. Moreover, the five earliest and latest GSS and GSE dates were compared, as well as the shortest and longest GS for each of the discussed stations.

Then, changes in the start and end, as well as the length of the GS in the analysed multiannual period were determined. The direction and rate of changes were assessed using linear regression, and trend significance was verified using a *t*-Student test at a level of 0.05. The study involved verification of the trend change points. The estimation of optimal breaks in the trend of long-term series, i.e. years pointing to a change in direction or trend intensity in shorter periods, employed the strucchange R package (Zeileis et al. 2002), where the procedure proposed by Bai and Perron (1998) was applied. Then, for the designated subperiods, the direction and rate of changes in the analysed parameters were determined.

Results

Growing season start

In the years 1893–2020, GSS was characterised by high year-to-year variability (Fig. 2). That variability was approximate in the analysed stations, although it was somewhat higher in cities located more southwards, i.e. in Prague (σ = 16.3 days) and Vienna (σ = 14.6 days). The maximum range of fluctuations in the analysed period was approximately 2 months, and in the case of two stations (Prague and Vienna), it exceeded even 3 months. The average GSS was observed in the second decade of March in Prague (12.03) and Vienna (13.03), and in the third decade of March in Kraków and Potsdam (21.03), Poznań (27.03), and Toruń (30.03). From the end of the 1990s, GSS was evidently recorded earlier than the average date from the entire multiannual period (Fig. 2).

Apart from Prague and Vienna, GS set in at the earliest, already in February, in 1990, and in the two aforementioned stations – in 2007 (Table 1). In Prague, the season set in at the earliest, already on 31 December of the preceding year, i.e. in 2006, and in Vienna – on 3 January. In four cities, the second earliest start of the season occurred in 2020, and also in February. Considering the five earliest dates of GS start, each station is dominated by dates from the 21st century (Table 1). It is particularly evident in Potsdam, where apart from 1990, the remaining dates come from the last two decades. In the remaining stations, years from outside of the 21st century are 1966, 1989, 1995, and 1998. Particular attention should be paid to 1938, when GSS occurred on 12 March in Toruń. It was the fourth most important date in that station. In Kraków, Potsdam, and Poznań, the date was within the top 10 of the earliest dates, in Vienna in the second 10, and in Prague only in the third 10.

The latest GS start (except for Prague) was recorded in 1929 and occurred in the majority of stations in the second half of April (Table 1). Moreover, in Vienna, the same start date, i.e. 7 April, was recorded in 1917. In that year, the latest start of the analysed season in Prague was also observed (12 April). The five dates of the latest GS start were dominated by those from the 20th century, particularly from its first half (Table 1). In two stations (Prague and Vienna), one of the dates was from the 19th century, specifically from 1900. No date from the 21st century was recorded in any of the analysed cities among the five latest GSS dates. In the last two decades, the latest GSS in all stations occurred at the end of March (Kraków, Prague, Vienna) and at the beginning of April 2013 (Potsdam, Poznań, Toruń).

In the period 1893–2020, an increasingly earlier GSS was observed. The most intensive changes occurred in Prague, where the calculated trend was −2.09 days per 10 years. In the remaining stations, these changes varied from −1.05 days/10 years in Potsdam to −1.63 days/10 years in Vienna (statistically significant). Detailed research showed the intensification of changes in GSS at the end of the 20th and in the 21st century. The analysis of the trend variability in shorter periods permitted the designation of two subperiods differing in change intensity. The point of change for most stations proved to be 1988, and in Kraków it occurred somewhat earlier, i.e. in 1971. In the second subperiod, a multiple times higher rate of changes was determined (Fig. 2).

Table 1. Five earliest and latest dates of GSS in the years 1893–2020. GSS, growing season start.

No.	Kraków	Potsdam	Poznań	Prague	Toruń	Vienna
earliest start						
1	10.02.1990	03.02.1990	11.02.1990	31.12.2006	19.02.1990	03.01.2007
2	14.02.2002 14.02.2016	06.02.2020	16.02.2020	28.01.2020	08.03.1989 08.03.2019	06.02.2020
3	16.02.2020	14.02.2002	26.02.2014	29.01.2008	09.03.2014	07.02.1998
4	21.02.1989	17.02.2014	03.03.1989	03.02.1998	12.03.1938	08.02.2002 08.02.2016
5	25.02.2014 25.02.2019	20.02.2019	04.03.2019	04.02.1990	13.03.2007	11.02.1966 11.02.1995
latest start						
1	18.04.1929	17.04.1929	20.04.1929	12.04.1917	23.04.1929	07.04.1929 07.04.1917
2	12.04.1958	14.04.1956 14.04.1917	18.04.1917	08.04.1929	21.04.1917	06.04.1958
3	11.04.1907	13.04.1958	17.04.1956	07.04.1958	19.04.1955	05.04.1931
4	10.04.1955 10.04.1931 10.04.1917	11.04.1931	16.04.1958 16.04.1931 16.04.1905	06.04.1931	18.04.1958 18.04.1956 18.04.1924	02.04.1907 02.04.1900
5	08.04.1942 08.04.1933	10.04.1970	14.04.1924 14.04.1902	03.04.1900	17.04.1954 17.04.1941 17.04.1931 17.04.1905	01.04.1955 01.04.1942

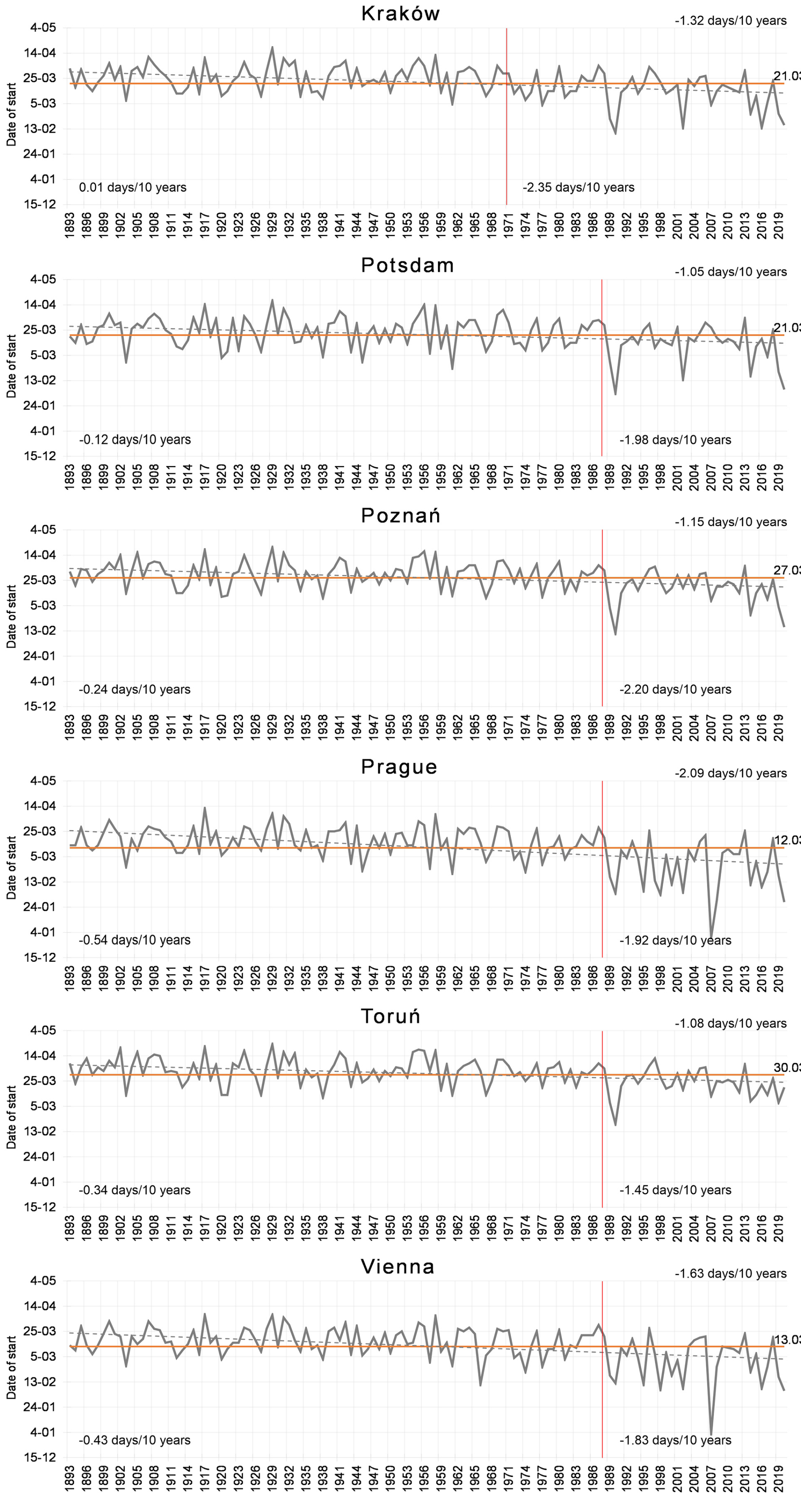

Fig. 2. GSS date with average date from the multiannual period (horizontal line), trend breaking point (vertical line), and direction and intensity of changes in 1893–2020 and subperiods. GSS, growing season start.

Growing season end

Like in the case of GSS, also the end date varied from year to year, although the maximum range of these fluctuations in the analysed multiannual period was lower than in the case of GSS (Fig. 3). The greatest variability of dates was recorded in Potsdam – slightly above 3 months. In the remaining stations, the variation was approximately 2 months. Year-to-year variability of GSE dates lower than in the case of GSS is also pointed to by lower standard deviation values, ranging from 10.2 (Toruń) to 13.2 days (Prague). On average in the analysed multiannual period, GS end was recorded in the first decade of November in Toruń (3.11), Poznań (5.11), Kraków (8.11), and Potsdam (9.11), and in the second decade of November in Vienna (13.11) and Prague (16.11). Two periods can be designated in the analysed multiannual period, i.e. until the mid 1920s, with most GSE dates below the average multiannual value, and from the beginning of the 21st century with dates above average (Fig. 3).

The earliest GSE was recorded at the beginning of the 20th century, i.e. in the years: 1902, 1905, 1919, 1920, and 1922 (Table 2). These dates occurred at the end of the first and at the beginning of the second decade of October in Toruń (10.10), Kraków (12.10), Potsdam, and Poznań (13.10), and in the third decade in Vienna (21.10) and Prague (26.10). A large majority of the five earliest GSE dates in the analysed multiannual period are years from the first two decades of the 20th century (Table 2). In the 19th century, there was one date in Prague (in the fourth position), whereas the date recorded the closest to the present moment was in 1965 (fifth position).

In the majority of stations, i.e. in four out of six, the latest date of GSE was recorded in the 21st century, i.e. in 2006 and 2015 (Table 2). In the remaining two stations (Prague and Vienna), the date was recorded in 1975 and 1934, respectively. The latest GSE usually occurred in the first and second decade of December, and in the case of Potsdam and Prague only in January of the following year, on 14 January 2007 (GSE from 2006 in Potsdam) and 5 January 1975 (GSE from 1974 in Prague), respectively (Table 2). A large majority of GSE dates in the analysed multiannual period were from the last 20 years (Table 2). This particularly concerns seasons from 2006, 2015, 2019, and 2020.

In the years 1893–2020, increasingly later GS end was recorded. The changes ranged from 1.00 day per 10 years in Vienna to 1.28 days per 10 years in Kraków. In all stations, the recorded changes were statistically significant. In the case of the same dates, two subperiods were designated differing in the intensity of changes (Fig. 3). In four stations (Potsdam, Poznań, Toruń, Vienna), the trend breaking point was 1999, and in the

Table 2. Five earliest and latest dates of GSE in the years 1893–2020. GSE, growing season end.

No.	Kraków	Potsdam	Poznań	Prague	Toruń	Vienna
earliest end						
1	12.10.1920	13.10.1905 13.10.1922	13.10.1905 13.10.1922	26.10.1902 26.10.1919 26.10.1922	10.10.1922	21.10.1920
2	13.101905	20.10.1920	15.10.1946	27.10.1905	11.10.1920	25.10.1912
3	16.10.1922 16.10.1946	21.10.1919	18.10.1915	28.10.1912 28.10.1915	14.10.1905	26.10.1902 26.10.1922
4	19.10.1912	22.10.1915	19.10.1912 19.10.1919 19.10.1920	29.10.1897 29.10.1908	15.10.1946	27.10.1905 27.10.1908
5	21.10.1908	23.10.1902	20.10.1902	30.10.1920 30.10.1965	19.10.1912 19.10.1919	28.10.1915 28.10.1941
latest start						
1	15.12.2015	14.01.2007	17.12.2015	05.01.1975	08.12.2015	15.12.1934
2	03.12.2006	22.12.2015	09.12.2006	28.12.2015	05.12.2006	08.12.2015
3	02.12.2019	16.12.1974	30.11.2019	20.12.2011	25.11.2019	06.12.2014
4	27.11.1926 27.11.1951	01.12.1951	25.11.1951 25.11.2020	17.12.2006	24.11.2000	04.12.2006 04.12.2019
5	26.11.2014	29.11.1994 29.11.2020	24.11.2000	15.12.1979	23.11.2020	29.11.1926 29.11.2000

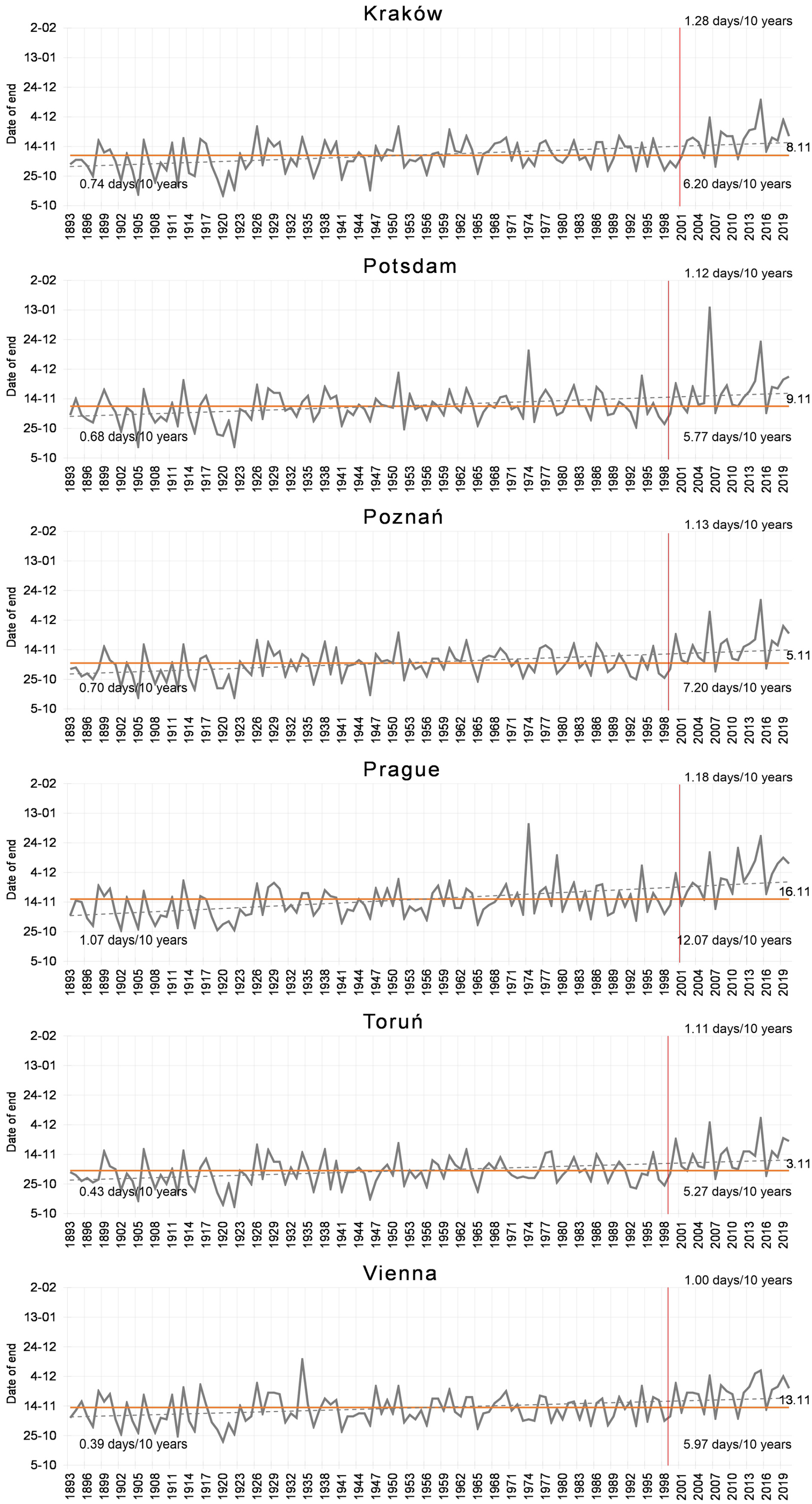

Fig. 3. GSE date with average date from the multiannual period (horizontal line), trend breaking point (vertical line), and the direction and intensity of changes in 1893–2020 and subperiods. GSE, growing season end.

remaining ones (Kraków, Prague) 2001. Like in the case of GSS, changes in the second subperiod were multiple times greater. The most intensive delay of the GSE date was recorded in Prague (12.07 days per 10 years) (Fig. 3).

Growing season length

In the years 1893–2020, the average GSL was from 219 days in Toruń to 250 days in Prague (Fig. 4) and varied from year to year from 181 days to 319 days (Table 3). The standard variation value, however, indicates that these fluctuations were approximate in most stations and ranged from 17 days to 19 days. Like in the case of GSS and GSE variability, the variability of its length was also the greatest in Prague (σ = 23 days). Considering extreme values, the range of the fluctuations was at least 3 months with a maximum in Prague, reaching three and a half months. In all stations, a large majority of GS from the 1990s lasted longer than on average in the multiannual period. It particularly concerned the second decade of the 21st century (Fig. 4).

Except for Prague and Vienna, the shortest GS lasted <200 days. Its minimum length (181 days) was observed in 1905 in Poznań and Toruń (Table 3). In Kraków and Potsdam, the shortest GS lasted <2 weeks longer, i.e. 194 days, respectively, in 1905 and 1922. In Vienna and Prague, the minimum GSL was the longest among the analysed stations, i.e. 213 days in 1931 and 214 days in 1915. The aforementioned situation was primarily caused by the early end of the GS. One of the three earliest GS end dates was recorded in the aforementioned years (except for in Vienna). Moreover, in Potsdam, Poznań, and Vienna, in the analysed years, one of five identified latest GS starts was recorded. In all stations, a large majority of the five shortest analysed seasons in the studied multiannual period occurred in the first half of the 20th century (Table 3).

Among the analysed stations, also in the case of the longest GS, two stations stand out, i.e. Prague and Vienna. In those stations, it lasted >300 days, and to be specific, 319 days and 308 days (Table 3). In the remaining stations, the maximum GSL did not exceed that threshold, and reached 297 days in Potsdam, 285 days in Kraków, 283 days in Poznań, and the least in Toruń, namely 270 days. According to the aforementioned data, in the first two stations, GS, i.e. conditions permitting plant development, can occur even on 87% and 84% of days in a year. In the years with the longest recorded GS, one of the earliest starts and/or latest ends of the season was observed. In two stations, i.e. in Potsdam and Poznań, both conditions were met, and it was the second earliest GS start, and fifth and fourth latest end in the analysed multiannual period, respectively. Among the five longest GS in the studied multiannual period, seasons from the 21st century were dominant. GS from outside the last two decades occurred in 1938, 1974, 1990, and 2000 (Table 3).

Table 3. Five shortest and longest (GSL, in days) in the years 1893–2020. GSL, growing season length.

No.	Kraków	Potsdam	Poznań	Prague	Toruń	Vienna
shortest GS (year)						
1	194 (1905)	194 (1922)	181 (1905)	214 (1915)	181 (1905)	213 (1931)
2	200 (1908)	198 (1905)	190 (1902)	216 (1919)	185 (1902)	215 (1908)
3	201 (1931)	201 (1956)	194 (1956)	217 (1908) 217 (1931)	186 (1922)	217 (1915)
4	203 (1902) 203 (1941)	202 (1915) 202 (1919) 202 (1941)	195 (1931) 195 (1941)	218 (1956) 218 (1965)	187 (1941)	218 (1956)
5	206 (1956)	206 (1908)	196 (1915)	219 (1917)	189 (1956)	219 (1907)
longest GS (year)						
1	285 (1990)	297(2020)	283 (2020)	319 (1974)	270 (2015)	308 (2007)
2	281 (2019)	290 (2006)	278 (2015)	317 (2020)	264 (1990)	294 (2020)
3	280 (2015)	285 (2015)	274 (1990)	315 (2007)	263 (2019)	291 (2019)
4	279 (2020)	283 (1990) 283 (1974) 283 (2014)	272 (2019)	306 (2008)	251 (1938)	289 (2002) 289 (2014)
5	278 (2002)	281 (2019)	269 (2014)	305 (2014)	250 (2014)	285 (2000)

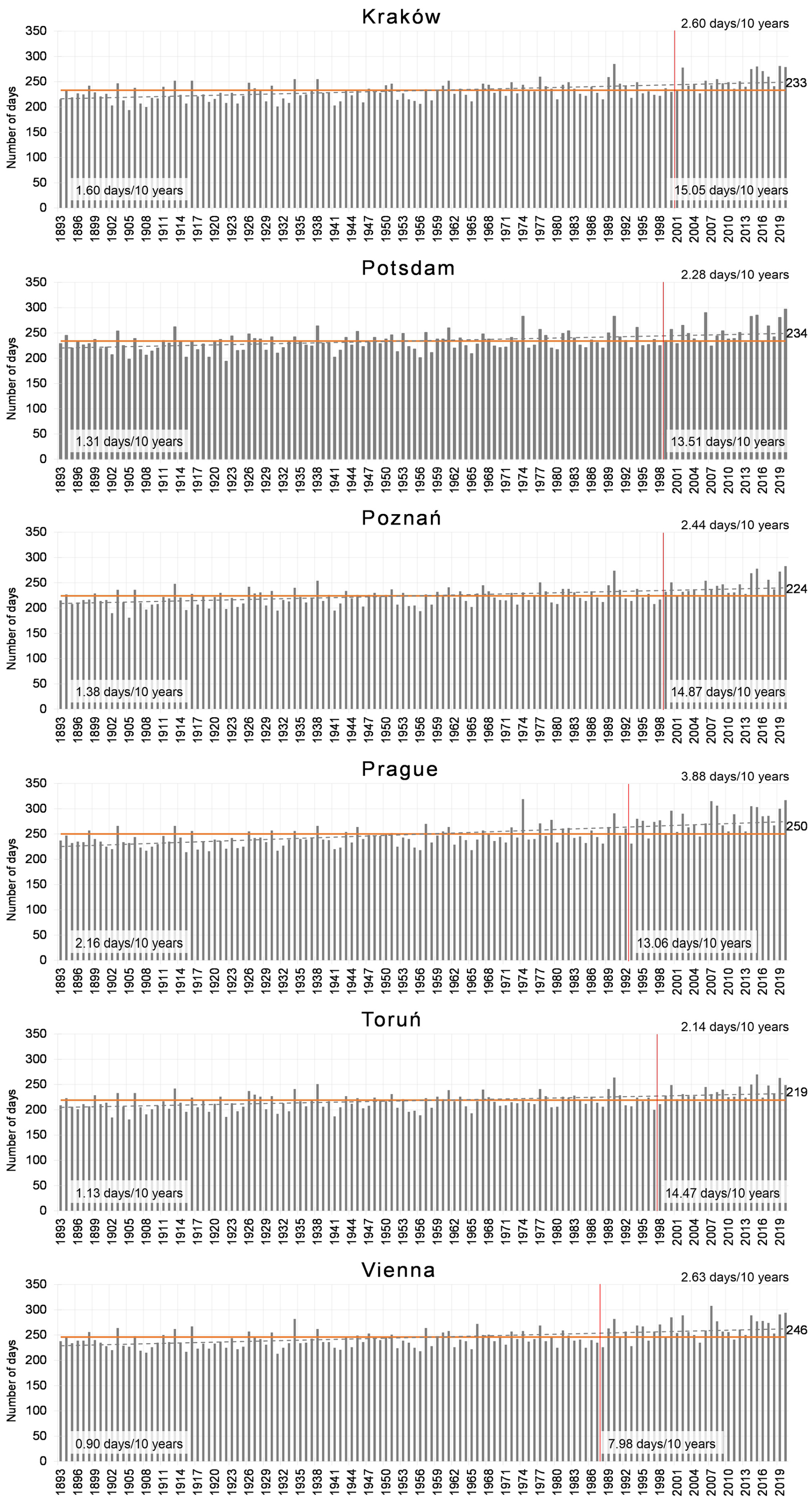

Fig. 4. GSL with the average date from the multiannual period (horizontal line), and the direction and intensity of changes (1893–2020). GSL, growing season length.

In the years 1893–2020, an increase in GSL was observed. The most intensive increase in its length was recorded in Prague, reaching 3.88 days per 10 years (Fig. 4). In the remaining stations, changes varied from 2.14 days per 10 years in Toruń to 2.63 days per 10 years in Vienna. All these changes were statistically significant, but their intensity varied in the analysed multiannual period. The study determined the occurrence of two subperiods, and the change point was 1988 in Vienna, 1993 in Prague, 1998 in Toruń, 1999 in Potsdam, and 2001 in Kraków. According to the above data, in Kraków, Potsdam, and Poznań, a change in GSL was largely determined by its end date, and in Vienna its start date. The rate of changes in the second subperiod, like in the case of GSS and GSE, was multiple times greater, ranging from 7.98 days per 10 years in Vienna to 15.05 days per 10 years in Kraków (Fig. 4).

Discussion

In the years 1893–2020, GSS in the analysed stations was characterised by high year-to-year variability, particularly in those located more southwards, i.e. in Prague and Vienna, where the standard deviation was 16.3 days and 14.6 days, respectively. The majority of the latest start dates occurred in the first half of the 20th century. Increasingly earlier GSS was observed from the 1990s in all the analysed stations except for Kraków, where the acceleration of changes occurred already at the beginning of the 1970s. The rate of changes in the analysed period ranged from 1.05 days/10 years in Potsdam to 2.09 days/10 years in Prague. It was determined that the intensification of the rate of the occurring changes was recorded in all stations at the end of the 20th and in the 21st century.

A smaller variability occurred in GSE dates in the years 1893–2020 in the analysed stations, as evidenced by lower values of the standard deviation, ranging from 10.2 days (Toruń) to 13.2 days (Prague). A delay in GSE occurred in all cities by an average from 1.0 day/10 years in Vienna to 1.28 days/10 years in Kraków. More intensive changes in GS end dates occurred at the turn of the 20th century and in the 21st century.

In the years 1893–2020 in selected stations in Central Europe, GSL lasted from 219 days in Toruń to 250 days in Prague and was characterised by approximate variability in all stations (standard deviation from 17 days to 19 days). The length of the analysed season increased in the studied cities from 2.14 days/10 years in Toruń to 3.88 days/10 years in Prague. An increase in season duration was also determined in different regions of Poland, among others by Skowera and Kopeć (2008), Tylkowski (2015), Graczyk and Kundzewicz (2016), Tomczyk and Szyga-Pluta (2019), Koźmiński et al. (2021). The greatest increase in GSL in Poland in the years 1966–2015 was determined at the coast (Szyga-Pluta, Tomczyk 2019), and in the years 1971–2020 in the west of the country (Koźmiński et al. 2021). The increasing tendency of GSL in the regions of coastal forest assemblages at the eastern Baltic coast decreases eastwards (Tylkowski 2015), and is higher than in north-eastern Europe, where it averages 1.5 days/10 years (Linderholm et al. 2008). A similar direction of changes was also observed in other regions of Europe (Carter 1998, Menzel et al. 2003, Jaagus 2006, Linderholm et al. 2008, Irannezhad, Kløve 2015, Potopova et al. 2015) and in China (Dong et al. 2013, Cui et al. 2017). An increase in GSL in Europe by 10.8 days from the 1960s based on 30-year-long observations was also determined by Menzel and Fabian (1999), as confirmed by later phenological observations (Menzel 2000, Stenseth et al. 2002), and by Walther and Linderholm (2006) by 20 days in the Baltic region. The length of the analysed season considerably increased in Eurasia (12.6 days in the years 1950–2011). In North America the change was smaller (6.2 days) (Barichivich et al. 2013). In the boreal and Arctic zone, GSL increased by 2.6 days per decade (in the years 1982–2014), whereas a greater rate of changes was observed in Eurasia and in boreal regions than in North America and Arctic regions (Park et al. 2016).

The rate of changes increased in Kraków, Potsdam, Poznań, and Toruń at the turn of the 20th century and in the 21st century, and in Prague and Vienna approximately a decade earlier. Earlier study results point to a similar tendency (Nieróbca et al. 2013, Tomczyk, Szyga-Pluta 2019). Nieróbca et al. (2013) calculated GSL using approximation of the value of multiannual daily temperature and determined that in the period 2001–2009, the season was longer by 8 days in comparison with that in the years 1971–2000.

This is also confirmed in phenological studies because over the last three decades, the thermal sensitivity of spring phenophases has also increased (Wang et al. 2014, Jabłońska et al. 2015). According to Liu et al. (2016), in the period 2000–2013 in comparison to the years 1986–1999, the tendency for prolongation of GS in China weakened. Results by Xia et al. (2013) show that in the years 1901–2009, an increase in GSL was weaker than estimated at the end of the second half of the 20th century due to the multidecadal variability of climate (MVC).

The causes of longer GS are not straightforward. In Toruń and Potsdam, its increase was caused by a somewhat greater shift of the end date, and in the remaining stations, it was determined by its earlier start date. Previous research of the authors in Poland points to a stronger effect of GSE delay on its longer duration (Tomczyk, Szyga-Pluta 2019). Such variability also occurred in Finland: in the north, the end was delayed, the beginning was early in the centre, and in the southwest coast, the shift of both GS start and end was the same (Irannezhad, Kløve 2015). Song et al. (2010) determined the prolongation of the GS primarily as a result of its start earlier by 1.7 days/10 years in northern China, and in the southern part, it was caused by an even shift of the start and end dates. In northern and central Europe, more considerable changes occurring in spring were observed based on phenological changes (Menzel 2000). It is therefore difficult to unequivocally predict the future state of the agroclimate and the resulting level of agricultural production, because irrespective of global tendencies, the role of local conditions will be substantial (Szwejkowski et al. 2017).

Phenological research conducted in the years 1951–1998 showed that in West and Central Europe the acceleration of spring phenophases of plants reached 4 weeks and their delay in East Europe reached 2 weeks (Ahas et al. 2002). An increase in GSL in Europe by 10.8 days from the 1960s based on 30-year-long observations was also determined by Menzel and Fabian (1999), as confirmed by later phenological observations (Menzel 2000, Stenseth et al. 2002). In the Czech Republic, as a result of earlier GS start and later end, the GS was prolonged by an average of 23.8 days over 35 years (Kolářová et al. 2014). Christidis et al. (2007) evidence that an increase in GSL is currently caused by its earlier start, although in the future the shift of both the start and end date will contribute to an increase in its length. Based on multiannual measurement series, the authors of this study determined that these changes occur increasingly faster, as already observed earlier by Song et al. (2010). According to Skaugen and Tveito (2004), the average GSL along the southern coast of Norway will be the same in the years 2021–2050 as in the southern part of Great Britain, Holland, and northern Germany in the years 1961–1998, i.e. approximately 200–210 days.

Earlier studies evidenced linear dependencies between air temperature and vegetation indices in different regions of the world (Xia et al. 2015). Regression results in different places around the globe show that an increase in mean air temperature by 1°C in a relevant combination of monthly values corresponds with a shift of GS in time (particularly its start) (Chmielewski et al. 2004, Piao et al. 2006, Dai et al. 2014, Ge et al. 2014, Wang et al. 2014). According to results by Karlsen et al. (2007), an increase in spring temperature by 1°C generally corresponds with a shift of GS start to 5–6 days earlier, but an evident regional tendency is observed depending on the degree of the oceanic character of the climate. An increase in temperature by 1°C in the oceanic climate corresponds to a shift of GS start to approximately 7–9 days earlier in comparison to <5 days earlier in the continental parts. Research conducted by Parmesan and Yohe (2003) revealed considerable shifts in the range of many plant and animal species by an average of 6.1 km per decade towards the poles (or metres per decade upwards) and considerable average acceleration of spring activity by 2.3 days per decade. The trend analysis by Czernecki and Jabłońska (2016) unequivocally points to the acceleration of the term of flowering of common lilac and European horse-chestnut by an average of 1.7 days per decade and is primarily caused by a rapid increase in temperature observed since the 1990s. In earlier decades, late spring phenophases showed no unequivocal change trends.

Changes in dates of occurrence of phenological changes are determined by temperature fluctuations dependent on changes in the circulation regime (Degirmendžić et al. 2000, Chmielewski, Rötzer 2002, Aasa et al. 2004). According to Bartoszek and Węgrzyn (2011), important predictors of GS start in East Poland include the North Atlantic Oscillation (NAO) index accounting for 13%–29% of its variability, and the year-to-year variability of GS start dates is related to the character of zonal circulation.

A considerable increase in temperature occurred among others in the warm season of the year. It translates into the prolongation of the intensive GS and a substantial increase of heat resources in the period of active plant growth (Żmudzka 2012). Bartoszek and Banasiewicz (2007) also determined that the tendency for the occurrence of GS warmer than the norm that was evident in Central Europe in the decade of 1991–2000 is still maintained. In GS in Poland in the period 1966–2015, greater changes in thermal conditions occurred (an increase in mean air temperature, an increase in air temperature total) than precipitation conditions (Tomczyk, Szyga-Pluta 2019).

Future agroclimatic scenarios developed based on global models show that the observed trends can still increase (Qian, Gameda 2010). Research by Xia et al. (2015) reveals that in the majority of terrestrial areas of the Northern Hemisphere, GS start will be from 4.7 to 10.1 earlier in the period 2040–2059 than in the years 1985–2004, and in the years 2080–2099 it will be from 4.3 days to 21.6 days earlier.

Conclusions

In the period 1893–2020 in Central Europe, GS was prolonged, although these changes in particular stations selected for the analysis occurred unevenly, and were simultaneously the result of different factors. Higher variability of the start of the analysed season occurred in stations in the south of the analysed area (Prague, Vienna). Smaller variability is observed for its end date. The prolongation of GS in Vienna and Prague was determined to the highest degree by its start date, and in the remaining stations – its later end. It is worth emphasising that in the years 1893–2020, two subperiods can be designated differing in the intensity of the rate of changes in the start, end dates, and length of GS. It intensified in all stations at the end of the 20th and in the 21st century. The rate of changes increased in Kraków, Potsdam, Poznań, and Toruń at the turn of the 20th century and the 21st century, and in Prague and Vienna approximately a decade earlier.

The knowledge of trends of changes in the GS is important for the development of plans of adaptation and mitigation of their potential effects, not only in the agricultural sector but also in urbanised areas, including cities analysed in this paper. The variability of the GS also affects the structure and function of ecosystems also occurring in cities.

The performed calculations can be useful for municipal services dealing with the strategy of adaptation to climate change, including those responsible for urban green areas and the choice of appropriate plant species in parks and other green areas.

Over the upcoming years, the observed changes in the GS in urbanised areas will not only have an increasingly strong impact on the phenology of green areas, but also have economic, epidemiological, and bioclimatic consequences to which they will need to adapt. Urban planners, not only of green areas, will have to undertake increasingly frequent strategic activities to mitigate those effects on the environment.

Acknowledgments

Authors thank the reviewers and the editors for their comments and suggestions.

Funding

No funding.

Author's contribution

KSP: conceptualization, data curation, formal analysis, investigation, project administration, writing – original draft, writing – review and editing, correspondence with editor; AMT: conceptualization, data curation, investigation, writing – original draft; KP: writing – introduction, investigation; EB: investigation, writing – original draft.

References

Aasa A., Jaagus J., Ahas R., Sepp M., 2004. The influence of atmospheric circulation on plant phenological phases in central and eastern Europe. *International Journal of Climatology* 24(12): 1551–1564. DOI 10.1002/joc.1066.

Ahas R., Aasa A., Menzel A., Fedotova V.G., Scheifinger H., 2002. Changes in European spring phenology. *International Journal of Climatology* 22: 1727–1738. DOI 10.1002/joc.818.

Backlund P., Schimel D., Janetos A., Hatfield J., Ryan M.G., Archer S.R., Lettenmaier D., 2008. Introduction. The effects of climate change on agriculture, land resources, water resources, and biodiversity in the United States, United States Climate Change Science Program Synthesis and Assessment Product 4.3: 11–20.

Bai J., Perron P., 1998. Estimating and testing linear models with multiple structural changes. *Econometrica* 66: 47–78. DOI 10.2307/2998540.

Barichivich J., Briffa K.R., Myneni R.B., Osborn T.J., Melvin T.M., Ciais P., Piao S., Tucker C., 2013. Large-scale variations in the vegetation growing season and annual cycle of atmospheric CO_2 at high northern latitudes from 1950 to 2011. *Global Change Biology* 19(10): 3167–3183. DOI 10.1111/gcb.12283.

Barnett T.P., Adam J.C., Lettenmaier D.P., 2005. Potential impacts of a warming climate on water availability in snow-dominated regions. *Nature* 438: 303–309. DOI 10.1038/nature04141.

Bartoszek K., Banasiewicz I., 2007. Agrometeorologiczna charakterystyka okresu wegetacyjnego w rejonie Lublina na tle wielolecia 1951-2005. *Acta Agrophysica* 9(2): 275–283.

Bartoszek K., Siłuch M., 2015. Porównanie metody Gumińskiego i teledetekcji satelitarnej w aspekcie wyznaczania dat początku okresu wegetacyjnego na obszarze Polski. *Inżynieria Ekologiczna* 45: 99–105.

Bartoszek, K., Węgrzyn A., 2011. Uwarunkowania cyrkulacyjne początku okresu wegetacyjnego w Polsce Wschodniej. *Annales UMCS* Section B 66(1): 93–102. DOI 10.2478/V10066-011-0006-Z.

Beniston M., 2003. Climatic change in mountain regions: A review of possible impacts. *Climatic Change* 59: 5–31. DOI 10.1023/A:1024458411589.

Bootsma A., 1994. Long term (100 yr) climate trends for agriculture at selected locations in Canada. *Climatic Change* 26: 65–88.

Carter T.R., 1998. Changes in the thermal growing season in Nordic countries during the past century and prospects for the future. *Agricultural and Food Science* Finland 7: 161–179. DOI 10.23986/afsci.72857.

Chen X., Tan Z., Schwartz M.D., Xu C., 2000. Determining the growing season of land vegetation on the basis of plant phenology and satellite data in Northern China. *International Journal of Biometeorology* 44: 97–101. DOI 10.1007/s004840000056.

Chmielewski F.M., Muller A., Bruns, E., 2004. Climate changes and trends in phenology of fruit trees and field crops in Germany, 1961–2000. *Agricultural and Forest Meteorology* 121: 69–78. DOI 10.1016/S0168-1923(03)00161-8.

Chmielewski F.M., Rötzer, T., 2002. Annual and spatial variability of the beginning of growing season in Europe in relation to air temperature changes. *Climate Research* 19: 257–264. DOI 10.3354/cr019257.

Christiansen D.E., Markstrom S.L., Hay L.E., 2011. Impacts of climate change on the growing season in the United States. *Earth Interactions* 15(33): 1–17. DOI 10.1175/2011EI376.1.

Christidis N., Stott P.A., Brown S., Karoly D.J., Caesar, J., 2007. Human contribution to the lengthening of the growing season during 1950–99. *Journal of Climate* 20(21): 5441–5454. DOI 10.1175/2007JCLI1568.1.

Cotton P.A., 2003. Avian migration phenology and global climate change. *Proceedings of the National Academy of Sciences USA* 100: 12219–12222. DOI 10.1073/pnas.1930548100.

Cui L., Shi J., 2021. Evaluation and comparison of growing season metrics in arid and semi-arid areas of northern China under climate change. *Ecological Indicators* 121: 107055. DOI 10.1016/j.ecolind.2020.107055.

Cui L., Shi J., Ma Y., Du H., 2017. Distribution and trend in the thermal growing season in China during 1961–2015. *Physical Geography* 38(6): 1–18. DOI 10.1080/02723646.2017.1344497.

Cui L., Shi J., Ma Y., Liu X., 2018. Variations of the thermal growing season during the period 1961–2015 in northern China. *Journal of Arid Land* 10(2): 264–276. DOI 10.1007/s40333-018-0001-6.

Czernecki B., Jabłońska K., 2016. Reconstruction of late spring phenophases in Poland and their response to climate change, 1951–2014. *Acta Agrobotanica* 69(2): 1671. DOI 10.5586/aa.1671.

Dai J.H., Wang H.J., Ge Q.S., 2014. The spatial pattern of leaf phenology and its response to climate change in China. *International Journal of Biometeorology* 58: 521–528. DOI 10.1007/s00484-013-0679-2.

Degirmendžić J., Kożuchowski K., Wibig, J., 2000. Epoki cyrkulacyjne XX wieku i zmienność typów cyrkulacji w Polsce. *Przegląd Geofzyczny* 45(3–4): 221–239.

Dong M.Y., Jiang Y., Zhang D.Y., Wu Z.F., 2013. Spatiotemporal change in the climatic growing season in Northeast China during 1960–2009. *Theoretical and Applied Climatology* 111(3): 693–701. DOI 10.1007/s00704-012-0706-y.

Duarte L., Teodoro A.C., Monteiro A.T., Cunha M., Gonçalvese H., 2018. QPhenoMetrics: an open source software application to assess vegetation phenology metrics. *Computers and Electronic in Agriculture* 148: 82–94. DOI 10.1016/j.compag.2018.03.007.

Fagre D.B., Charles C.W., Allen C.D., Birkeland C., Chapin F.S., Groffman P.M., Guntenspergen G.R., Knapp A.K.; McGuire A.D., Mulholland P.J., Peters D.P.C., Roby D.D., Sugihara G., 2009. Case studies. Thresholds of climate change in ecosystems, United States Climate Change Science Program Synthesis and Assessment Product 4.2: 15–34.

Frich P., Alexander L., Della-Marta P., Gleason B., Haylock M., Klein Tank A.M.G., Peterson T.C., 2002. Observed coherent changes in climatic extremes during the second half of the twentieth century. *Climate Research* 19: 193–212. DOI 10.3354/cr019193.

Ge Q.S., Wang H.J., Rutishauser T., Dai J.H., 2014. Phenological response to climate change in China: A meta-analysis. *Global Change Biology* 21(1): 265–274. DOI 10.1111/gcb.12648.

Graczyk D., Kundzewicz Z.W., 2016. Changes of temperature-related agroclimatic indices in Poland. *Theoretical and Applied Climatology* 124: 401–410. DOI 10.1007/s00704-015-1429-7.

Groisman P.Y., Knight R.W., Karl T.R., Easterling D.R., Sun B., Lawrimore J.H., 2004. Contemporary changes of the hydrological cycle over the contiguous United States: Trends derived from in situ observations. *Journal of Hydrometeorology* 5: 64–85. DOI 10.1175/1525-7541(2004)005<0064:CCOTHC>2.0.CO;2.

Gumiński R., 1948. Próba wydzielenia dzielnic rolniczo-klimatycznych w Polsce. *Przegląd Meteorologiczno-Hydrologiczny* 1: 7–20.

Haggerty B.P., Mazer S.J., 2008. *The phenology handbook*. Phenology Stewardship Program Report, University of California, Santa Barbara: 1–43.

Irannezhad M., Kløve, B., 2015. Do atmospheric teleconnection patterns explain variations and trends in thermal growing season parameters in Finland? *International Journal of Climatology* 35(15): 4619–4630. DOI 10.1002/joc.4311.

Jaagus, J., 2006. Climatic changes in Estonia during the second half of the 20th century in relationship with changes in large-scale atmospheric circulation. *Theoretical and Applied Climatology* 83: 77–88. DOI 10.1007/s00704-005-0161-0.

Jabłońska K., Kwiatkowska-Falińska A., Czernecki B., Walawender J.P., 2015. Changes in spring and summer phenology in Poland – Responses of selected plant species to air temperature variations. *Polish Journal of Ecology* 63(3): 311–319. DOI 10.3161/15052249PJE2015.63.3.002.

Janetos A., Hansen L., Inouye D., Kelly B.P., Meyerson L., Peterson B., Shaw R., 2008. Biodiversity. The effects of climate change on agriculture, land resources, water resources, and biodiversity in the United States, United States Climate Change Science Program Synthesis and Assessment Product 4.3: 151–182.

Jones P.D., Briffa K.R., Osborn T.J., Moberg A., Bergström, H., 2002. Relationships between circulation strength and the variability of growing-season and cold-season climate in northern and central Europe. *Holocene* 12: 643–656. DOI 10.1191/0959683602hl577rp.

Jones P.D., Briffa, K.R., 1995. Growing season temperatures over the former Soviet Union. *International Journal of Climatology* 151: 943–959.

Karlsen S.R., Solheim I., Beck P.S., Høgda K.A., Wielgolaski F.E., Tømmervik H., 2007. Variability of the start of the growing season in Fennoscandia, 1982–2002. *International Journal of Biometeorology* 51(6): 513–524. DOI 10.1007/s00484-007-0091-x.

Kępińska-Kasprzak M., Mager, P., 2015. Thermal growing season in Poland calculated by two different methods. *Annals of Warsaw University of Life Sciences-SGGW Land Reclamation* 47(3): 261–273. DOI 10.1515/sggw-2015-0030.

Kexin Z., Xiaogang D., Jiaoting P., Zhihua S., Yanhong Z., 2021. Analysis of changes in thermal growing season and their relationships with atmospheric teleconnection patterns for the Yellow River basin in China. *Physical Geography* 42(2): 183–198. DOI 10.1080/02723646.2020.1799539.

Kolářová E., Nekovář J., Adamík, P., 2014. Long-term temporal changes in central European tree phenology (1946−2010) confirm the recent extension of growing seasons. *International Journal of Biometeorology* 58(8): 1739–1748. DOI 10.1007/s00484-013-0779-z.

Kolendowicz L., Czernecki B., Półrolniczak M., Taszarek M., Tomczyk A.M., Szyga-Pluta K., 2019. Homogenization of air temperature and its long-term trends in Poznań (Poland) for the period 1848–2016. *Theoretical and Applied Climatology* 136: 1357–1370. DOI 10.1007/s00704-018-2560-z.

Koźmiński C., Nidzgorska-Lencewicz J., Mąkosza A., Michalska B., 2021. Ground frosts in Poland in the growing season. *Agriculture* 11(7): 573. DOI 10.3390/agriculture11070573.

Linderholm H.W., 2006. Growing season changes in the last century. *Agricultural and Forest Meteorology* 137(1): 1–14. DOI 10.1016/j.agrformet.2006.03.006.

Linderholm H.W., Walther A., Chen D., 2008. Twentieth-century trends in the thermal growing season in the Greater Baltic area. *Climatic Change* 87: 405–419. DOI 10.1007/s10584-007-9327-3.

Liu X., Zhu X., Pan Y., Zhu W., Zhang J., Zhang, D., 2016. Thermal growing season and response of alpine grassland to climate variability across the Three-Rivers Headwater Region, China. *Agricultural and Forest Meteorology* 220: 30–37. DOI 10.1016/j.agrformet.2016.01.015.

Logan J.A., Regniere J., Powell J.A., 2003. Assessing the impacts of global warming on forest pest dynamics. *Frontiers in Ecology and the Environment* 1: 130–137. DOI 10.1890/1540-9295(2003)001[0130:ATIOGW]2.0.CO;2.

Menzel A., 2000: Trends in phenological phases in Europe between 1951 and 1996. *International Journal of Biometeorology* 44: 76–81. DOI 10.1007/s004840000054.

Menzel A., Estrella N., Heitland W., Susnik A., Schleip C., Dose V., 2008. Bayesian analysis of the species-specific lengthening of the growing season in two European countries and the influence of an insect pest. *International Journal of Biometeorology* 52(3): 209–218. DOI 10.1007/s00484-007-0113-8.

Menzel A., Fabian P., 1999. Growing season extended in Europe. *Nature* 397: 659–659. DOI 10.1038/17709.

Menzel A., Jakobi G., Ahas R., Scheifinger H., Estrella N., 2003. Variations of the climatological growing season (1951–2000) in Germany compared with other countries. *International Journal of Climatology* 23: 793–812. DOI 10.1002/joc.915.

Nicholls N., 2005. Climate variability, climate change and the Australian snow season. *Australian Meteorological Magazine* 54: 177–185.

Nieróbca A., Kozyra J., Mizak K., Wróblewska, E., 2013. Zmiana długości okresu wegetacyjnego w Polsce. *Woda-Środowisko-Obszary Wiejskie* 13(2): 81–94.

Park T., Ganguly S., Tømmervik H., Euskirchen E.S., Høgda K.A., Karlsen S.R., Brovkin V., Nemani R.R., Myneni R.B., 2016. Changes in growing season duration and productivity of northern vegetation inferred from long-term remote sensing data. *Environmental Research Letters* 11(8): 084001. Online: iopscience.iop.org/1748-9326/11/8/084001 (accessed 31 August 2022).

Parmesan C., Yohe G., 2003. A globally coherent fingerprint of climate change impacts across natural systems. *Nature* 421: 37–42. DOI 10.1038/nature01286.

Peng D., Wu C., Li C., Zhang X., Liu Z., Ye H., Luo S., Liu X., Hu Y., Fang, B., 2017. Spring green-up phenology products derived from MODIS NDVI and EVI: Intercomparison, interpretation and validation using National Phenology Network and AmeriFlux observations. *Ecological Indicators* 77: 323–336. DOI 10.1016/j.ecolind.2017.02.024.

Peng S., Huang J., Sheehy J.E., Laza R.C., Visperas R.M., Zhong X., Centeno G.S., Khush G.S., Cassman K.G., 2004. Rice yields decline with higher night temperature from global warming. *Proceedings of the National Academy of Sciences USA* 101: 9971–9975. DOI 10.1073/pnas.0403720101.

Peterson B.J., Holmes R.M., McClelland J.W., Vorosmarty C.J., Lammers R.B., Shiklomanov A.I., Shiklomanov I.A., Rahmstorf S., 2002. Increasing river discharge to the Arctic Ocean. *Science* 298: 2171–2173. DOI 10.1126/science.1077445.

Piao S.L., Fang J.Y., Zhou L.M., Ciais P., Zhu B., 2006. Variations in satellite-derived phenology in China's temperate vegetation. *Global Change Biology* 12: 672–685. DOI 10.1111/j.1365-2486.2006.01123.x.

Pospieszyńska A., Przybylak R., 2019. Air temperature changes in Toruń (central Poland) from 1871 to 2010. *Theoretical and Applied Climatology* 135: 707–724. DOI 10.1007/s00704-018-2413-9.

Potopova V., Zahradnicek P., Turkott L., Stepanek P., Soukup J., 2015. The effects of climate change on variability of the growing seasons in the Elbe River Lowland, Czech Republic. *Advances in Meteorology:* Article ID 546920. DOI 10.1155/2015/546920.

Qian C., Fu C.B., Wu Z.H., Yan Z.W., 2009. On the secular change of spring onset at Stockholm. *Geophysical Research Letters* 36: L12706. DOI 10.1029/2009GL038617.

Qian, B., Gameda, S., 2010. Canadian agroclimatic scenarios projected from a global climate model. 90th American Meteorological Society Annual Meeting, January 17–21, Atlanta, Georgia. Online: ams.confex.com/ams/pdfpapers/165170.pdf (accessed 31 August 2022).

Ryan M.G., Archer S.R., 2008. Land resources: Forest and arid lands. The effects of climate change on agriculture, land resources, water resources, and biodiversity in the United States, United States Climate Change Science Program Synthesis and Assessment Product 4.3: 75–120.

Skaugen T.E., Tveito O.E., 2004. Growing-season and degree-day scenario in Norway for 2021-2050. *Climate Research* 26(3): 221–232. DOI 10.3354/cr026221.

Skowera B., Kopeć B., 2008. Okresy termiczne w Polsce południowo-wschodniej (1971–2000). *Acta Agrophysica* 12(2): 517–526.

Song Y., Linderholm H.W., Chen D., Walther A., 2009. Trends of the thermal growing season in China. 1951–2007. *International Journal of Climatology* 30: 33–43. DOI 10.1002/joc.1868.

Stenseth N.C., Mysterud A., Ottersen G., Hurrel J.W., Chan K.S., Lima, M., 2002. Ecological effects of climate fluctuations. *Science* 297: 1292–1296. DOI 10.1126/science.1071281.

Studer S., Stöckli R., Appenzeller C., Vidale P.L., 2007. A comparative study of satellite and ground-based phenology. *International Journal of Biometeorology* 51: 405–414. DOI 10.1007/s00484-006-0080-5.

Szwejkowski Z., Kuchar L., Dragańska E., Cymes I., Cymes I., 2017: Current and future agroclimate conditions in Poland in perspective of climate change. *Acta Agrophysica* 24(2): 355–364.

Szyga-Pluta K., 2011. Termiczne pory roku w Poznaniu w latach 2001-2008. *Przegląd Geograficzny* 83(1): 109–119. DOI 10.7163/PrzG.2011.1.6.

Szyga-Pluta K., Tomczyk A.M., 2019. Anomalies in the length of the growing season in Poland in the period 1966–2015. *Időjárás* 123(3): 391–408. DOI 10.28974/idojaras.2019.3.8.

Tomczyk A.M., Szyga-Pluta K., 2019. Variability of thermal and precipitation conditions in the growing season in Poland in the years 1966–2015. *Theoretical and Applied Climatology* 135: 1517–1530. DOI 10.1007/s00704-018-2450-4.

Tylkowski J., 2015. The variability of climatic vegetative seasons and thermal resources at the Polish Baltic Sea coastline in the context of potential composition of coastal forest communities. *Baltic Forestry* 21: 73–82.

Walther A., Linderholm H.W., 2006. A comparison of growing season indices for the Greater Baltic Area. *International Journal of Biometeorology* 51(2): 107–118. DOI 10.1007/s00484-006-0048-5.

Wang H.J., Dai J.H., Zheng J.Z., Ge Q.S., 2014. Temperature sensitivity of plant phenology in temperate and subtropical regions of China from 1850–2009. *International Journal of Climatology* 35(6): 913–922. DOI 10.1002/joc.4026.

Xia J., Yan Z., Jia G., Zeng H., Jones P.D., Zhou W., Zhang, A., 2015. Projections of the advance in the start of the growing season during the 21st century based on CMIP5 simulations. *Advances in Atmospheric Sciences* 32(6): 831–838. DOI 10.1007/s00376-014-4125-0.

Xia J., Yan Z., Wu P., 2013. Multidecadal variability in local growing season during 1901–2009. *Climate Dynamics* 41(2): 295–305. DOI 10.1007/s00382-012-1438-5.

Zeileis A., Leisch F., Hornik K., Kleiber C., 2002. Strucchange: An R package for testing for structural change in linear regression models. *Journal of Statistical Software* 7(2): 1–38. DOI 10.18637/jss.v007.i02.

Żmudzka E., 2012. Wieloletnie zmiany zasobów termicznych w okresie wegetacyjnym i aktywnego wzrostu roślin w Polsce. *Woda-Środowisko-Obszary Wiejskie* 12(2): 377–389.