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RESEARCH ARTICLE - ATMOSPHERIC & SPACE SCIENCES

Past and future changes in the start, end, and duration of the growing season in Poland

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Abstract

The aim of the study was to determine the direction and rate of the projected changes of the start, end, and duration of the growing season in Poland in two-time horizons: 2021–2050 and 2071–2100. The main part of the paper was preceded by an analysis of changes in the start and end dates and the duration of the growing season in Poland in the period 1966–2020. The growing season in Poland is projected to be the shortest in mountain areas and in the north-eastern regions of Poland, where the date of growing season start is the latest and the date of the growing season end is the earliest. Whereas the longest growing season due to the projected earliest start and latest end dates is expected in the southwestern Poland. In the case of the coast, its late end will be of the greatest importance for its duration as a result of the warming effect of the sea in the autumn–winter period. The most intensive changes are forecasted in the long-term perspective in the case of the scenario regarding a high level of greenhouse gas emissions. The forecasts show that outside mountain areas, the growing season duration will vary from less than 255 days in the northeastern regions to more than 290 days in southwest and western Poland. In the duration of the mountains, the growing season will vary from 180 days on Kasprowy Wierch to 188 days on Śnieżka. This suggests significant changes in agroclimatic conditions in Poland.

Keywords Growing season · Climate change · Poland · Projections of changes · RCP's scenarios

Introduction

The modern climate change has a significant impact on human life and the natural environment in many respects. Increased air temperature (IPCC 2021) also known to affect vegetation development, including its considerable impact on the start, end, and duration of the growing season. Changes in vegetation dynamics and the long-term biological effects of climate change are considered to be one of the best indicators of plant dynamics and long-term biological effects of climate change (Peng et al. 2017; Duarte et al. 2018; Cui and Shi 2021). An increase in temperature over 2 °C will probably result in a reduction in harvests of the main cereal crops (Easterling et al. 2007). Several climate forecasts for 2050 point to the exceedance of the threshold of 2 °C (Giorgi and Lionello 2008). According to Alcamo et al. (2007), the effects of climate change and the increase in CO_2 level in the atmosphere by 2050 will lead to a slight increase in the yields of European crops. The expected climate-related increases in crop yields in northern Europe are predicted for, e.g., wheat: + 2 to + 9% by 2020, + 8 to + 25% by 2050, + 10 to + 30% by 2080 (Alexandrov et al. 2002; Olesen et al. 2007). In southern Europe, general decreases in yield (e.g., legumes − 30 to + 5%; sunflower − 12 to + 3% and tuber crops − 14 to + 7% by 2050) and increases in water demand (e.g., for maize + 2 to + 4% and potato + 6 to + 10% by 2050) are expected for spring sown-crops (Giannakopoulos et al. 2005; Audsley et al. 2006). The increasing trend in temperature in the growing season occurred among others in Poland (Kaszewski 2000; Bochenek et al. 2013; Radzka 2014b; Ziernicka-Wojtaszek et al. 2015). A consequence of an increase in air temperature is the prolongation of the

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growing season in Europe, causing a modification of phenological stages of particular crops (Menzel and Fabian 1999; Chmielewski and Rötzer 2001; Chmielewski et al. 2004). An increase in air temperature correlates with other climatic and environmental parameters and, most importantly, meets a response in both natural and developed ecosystems at different levels, as well as in agriculture (Bootsma 1994; Karing et al. 1999; Schwartz et al. 2006).

Studies of changes in the parameters of the growing season usually focus on determining the trend of changes and/or their forecasts, taking into account the individual characteristics of the season, and indicate the need to adapt crops to these changes (Chmielewski and Rötzer 2002; Chmielewski et al. 2004; Linderholm 2006; Jeong et al. 2011; Kolářová et al. 2014; Xia et al. 2015; Cui et al. 2017; Vega et al. 2020; Koźmiński et al. 2021; Zhu et al. 2021). These studies use a series of air temperature measurements, phenological observations or satellite images (Walther and Linderholm 2006; Cui and Shi 2021). It was found, among others, that in the years 1901–2009 in the Northern Hemisphere, the length of the growing season lengthened, mainly due to earlier start dates, but the trend of change was weaker than in the second half of the 20th century (Xia et al. 2013). Between 1950 and 2011, the growing season lengthened in Eurasia by 12.6 days, and in North America by 6.2 days (Barichivich et al. 2013). Research by Walther and Linderholm (2006) shows that in the 20th century, in the area of the Baltic Sea, the growing season was extended by 20 days (12 days earlier start date and 8 days later end date). In Poland, based on data from 1971–2010, a change of 4–8 days per 10 years was determined (Tomczyk and Szyga-Pluta 2016), and in years 1971–2020 at a level of 5–7 days per decade, while a higher rate of extension of the season was observed in the west of the country (Koźmiński et al. 2021). The results confirmed the previously established trend for extending the growing season in Poland and selected regions of Poland (Żmudzka and Dobrowolska 2001; Nieróbca et al. 2013; Krużel et al. 2015).

Further migration of climatic zones northwards is forecasted over the majority of the European territory, and the transformed climatic conditions will modify the agroclimatic resources. In the foreseeable future, agriculture will evolve through adjustments to climate change (Reddy and Hodges 2000; Olesen et al. 2011; Mall et al. 2006; Trnka et al. 2011). There is a possibility of a decrease in the agricultural efficiency of atmospheric precipitation as a result of more intensive evaporation caused by an increase in air temperature in the context of a lack of evident trends of atmospheric precipitation (Ziernicka-Wojtaszek 2009). In the temperate zone, it may restrict the growth of plants due to among others the alternate occurrence in a given area of both water deficits and floods and more frequent occurrence of intensive droughts and precipitation deficits in the growing season (Førland et al. 2004; Pińskwar 2010; Szwed et al. 2010; Radzka 2014a; Piniewski et al. 2020; Jiao et al. 2021). At the beginning of the 20th century, a trend was observed involving a decrease in the share of summer precipitation in the annual precipitation total, in accordance with the projections of IPCC, and atmospheric precipitation totals strongly significantly affected the yield of harvests of selected crops (Żarski et al. 2014). A reduction in the productivity of certain crops can result from thermal stress and a deterioration of the water balance, including potatoes (Rykaczewska 2015) or rice (Peng et al. 2004). Jaggard et al. (2007) evaluated the impact of climate changes on beet production in the UK, and found that weather changes, especially at the beginning of the growing season, results in better yields. Growing season shifts of 10–14 days expected over the next 30 years, according to, e.g., Eitzinger et al. (2013), would be unprecedented in the context of the long-term study series by Brázdil et al. (2019). Ceglar et al. (2019) predict that in the coming decades, the migration of agroclimatic zones in Eastern Europe could more than double the rate observed in the period 1975–2016, which would result in some Mediterranean regions losing their ability to grow certain crops in favor of new agricultural areas in the north Europe. Warmer growing seasons in Finland are already causing temporal and spatial modifications of crops and their varieties (Peltonen-Sainio and Jauhiainen 2020). However, Ceglar et al. (2019) also show that the potential benefits of extending the thermal growing season in Northern and Eastern Europe are often associated with a risk of late frosts and an increased risk of early spring and summer hot days. According to Trnka et al. (2011), both the rate and the scale of changes in agroclimatic zones are astonishing, because by 2050 (assuming the upper range of climate change forecasts) it may be less than 2% of arable land in the analyzed region would remain in the same agroclimate.

Future agroclimate scenarios based on global models show that the observed trends may intensify even further (Qian and Gameda 2010). In the projections, the extension of the growing season varies from 15 to 30 days in the near future to 60 days in the late 21st century for the RCP8.5 emissions scenario (Wibig 2020; Graczyk et al. 2021). There are significant regional differences in the expected impact of climate change on European crops and yields by 2050 (Olesen et al. 2011). Therefore, it is difficult to accurately predict the future state of the agroclimate and the resulting level of agricultural production, because regardless of global trends, the role of local factors will be significant (Szwejkowski et al. 2017). In response to future global warming of 1.5 °C and 2 °C, science-based management and adaptation is essential to optimize agricultural production locally and regionally (Zhou et al. 2018).

The objective of this paper is the determination of the direction and rate of the projected changes of the start, end, and duration of the growing season in Poland in two time horizons: 2021–2050 and 2071–2100. The main part of the paper was preceded by the analysis of changes in start and end dates and duration of the growing season in Poland in the period 1966–2020.

Materials and methods

The investigation was based on monthly air temperature values obtained from 42 stations in Poland (Fig. 1) for the period 1966–2020. The data, verified for uniformity and homogeneity, was obtained from the Institute of Meteorology and Water Management—National Research Institute.

The above data provided the basis for determining, in the first place, the dates of the beginning and end of the growing season, understood as a period with an average daily air temperature of > 5 °C. This definition has been previously adopted in many studies (Carter 1998; Skaugen and Tveito 2004; Linderholm et al. 2008). Mathematical formulas proposed by Gumiński (1948) were used to determine the start and end dates of the growing season. The method is based on the following assumptions: the average monthly temperature occurs on the 15th of the month, each month has 30 days, and the temperature changes from month to month occur evenly. The following formulas were used:

$$x = 30\frac{tp - t1}{t2 - t1} \text{ for growing season start}$$

$$x = 30\frac{t1 - tp}{t1 - t2} \text{ for growing season end,}$$

where *tp*—threshold temperature (5 °C); *t1*—mean temperature in the month preceding the threshold temperature; *t2*—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 higher than 15, the addition should consider the actual number of days in a given month. The obtained date is the growing season start or end. The described method is commonly adopted in the determination of the growing season as well as the other thermal seasons of the year (e.g., Skowera and Kopeć 2008; Szyga-Pluta 2011; Kępińska-Kasprzak and Mager 2015; Tomczyk and Szyga-Pluta 2019). Bartoszek and Siłuch (2015) evidenced considerable conformity of average growing season start dates determined using the Gumiński (1948) method and satellite remote sensing in the decade 2001–2010.

In order to examine future changes in the start and end dates and the length of the growing season in Poland, we used temperature projections from an ensemble of nine bias-corrected regional climate models (Mezghani et al. 2017). Two Radiative Concentration Pathways (RCPs) and future time horizons were considered. RCPs denote plausible pathways toward reaching particular target radiative forcing trajectories (Moss et al. 2010). The RCPs used in

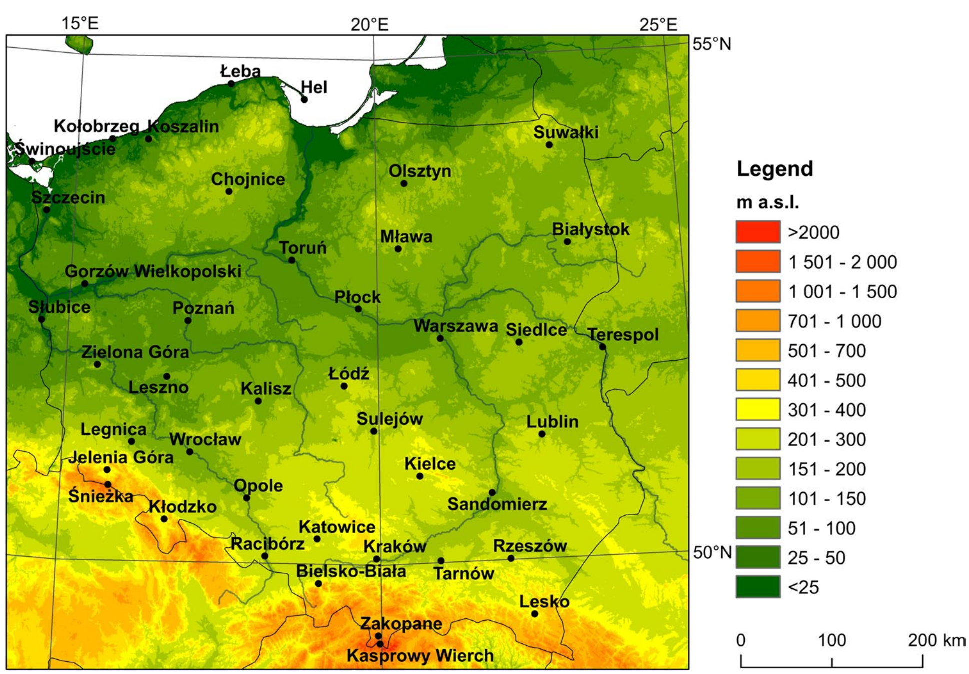

Fig. 1 Locations of meteorological stations

this article, RCP4.5 and 8.5, correspond to the 4.5 W/m^{-2} and 8.5 W/m^{-2} levels of radiative forcing in year 2100, respectively. In this study, bias-corrected EURO-CORDEX projections developed in the framework of the CHASE-PL project (Kundzewicz et al. 2018; Mezghani et al. 2017) were used. Spatial resolution of the original EURO-CORDEX projections was 0.11 degrees; however, within the bias-correction process (Mezghani et al. 2017) they were interpolated over the 5 km resolution domain. The project resources did not allow for including all four RCPs, so the focus was put on the high end (continuation of the business-as-usual) RCP8.5 and the intermediate, yet very popular in research RCP4.5. RCP6.0 can be considered as something in between 4.5 and 8.5 (closer to 4.5), so including this one would be partly redundant. Projected changes estimated from the multi-model ensemble mean showed that annual means of temperature are expected to increase steadily by 1 °C until 2021–2050 and by 2 °C until 2071–2100 assuming the RCP4.5 emission scenario. Assuming the RCP8.5 emission scenario, this can reach up to almost 4 °C by 2071–2100 (Mezghani et al. 2017). The time horizons were denoted as "near future" (NF), 2021–2050 and "far future" (FF), 2071–2100. The reference period was 1971–2000.

Results

Start, end, and duration of the growing season in the period 1966–2020

In the period 1966–2020, the growing season in Poland began on average on March 29 and ended on November 5. The beginning of the growing season took place from the south-west toward the north and north-east of Poland (Fig. 2). The earliest start of the growing season was recorded in Wrocław and Słubice—March 17, the latest in Suwałki—April 6 and in the mountains at Kasprowy Wierch—on June 4. The end of the growing season came from the north-east toward the southwest, as well as at the coast (Fig. 2). The end date of the analyzed period ranged from September 9 at Kasprowy Wierch and October 25 in Suwałki to November 17 in Hel and Kołobrzeg. The obtained data show that outside mountainous areas, the growing season started the earliest and ended the latest in south-western Poland, and started the latest and ended the earliest in north-eastern Poland. In the analyzed long-term period in Poland, the 1st day of the growing season occurred on December 30, 2020 in Szczecin at the earliest, on May 5, 1970 in Kołobrzeg and on May 5, 1980 in Zakopane, and the latest on Kasprowy Wierch on July 17, 1984. The last day of the growing season was recorded the earliest on October 2,1972 in Zakopane and on October 8, 1977 in Terespol, and in Świnoujście on January 16, 2006 the latest.

The mean duration of the growing season in Poland in the period 1966–2020 was 222 days. An increase in the duration of the season progressed from the northeast toward the southwest. In the mountains, the growing season was the shortest: on Kasprowy Wierch, it lasted for an average of 96 days, and on Śnieżka 116 days. Over the remaining territory of Poland, the average duration of the season varied from 203 days in Suwałki to 243 days in Szczecin (Fig. 2). The variability of the duration was approximate over a prevalent area of the country, as suggested by the standard deviation values that outside of the mountain stations were in a range of 14–16 days in central and east Poland, 16–21 days in the southwest and west of the country, and 19–22 days at the coast. In the analyzed multiannual period, the shortest growing season lasted 162 days in 1991 in Zakopane and 179 days in 1992 in Suwałki. The longest season lasted 336 days in 2020 in Szczecin. The research pointed to an increase in the duration of the growing season by an average of 4.8 days/10 years. The highest increase in growing season duration was recorded in north Poland, and particularly in seaside stations, namely in Hel (7.3 days/10 years) and Łeba (6.9 days/10 years), as well as on Kasprowy Wierch (6.9 days/10 years).

Start and end of the growing season in the near (2021–2050) and far (2071–2100) future

The study showed that over the subsequent decades, the growing season is projected to start increasingly early (Fig. 3). On average, in Poland, in the short-term perspective, its start will be recorded approximately 6 days earlier in the case of RCP4.5, and approximately 8 days earlier for RCP8.5. Both scenarios of greenhouse gas emissions show relatively low spatial variability of deviations from average values from the reference period, reaching 3.8 days for RCP4.5 and 3.3 days for RCP8.5. The highest deviations from the average will be observed in the northern regions of the country, at the coast. In RCP4.5, the changes will exceed 7 days (maximum in Hel 8.2 days), and in RCP8.5, nine days (maximum in Hel 10 days). The lowest deviations will occur in the first scenario in central regions (approximately and below 5 days) and in the other one in southwestern regions (below 7 days). In the short-term perspective, the greatest differences between changes in RCP4.5 and RCP8.5 were recorded in the northern regions and the smallest in the southwestern regions of the country.

In the long-term perspective, changes in the growing season start date will occur considerably more intensively than in the short term. It is projected that, on average, in RCP4.5, the growing season start date will occur 13 days earlier, and in RCP8.5, 25 days earlier (Table 1). In the former scenario, the most intensive changes will be observed in north Poland (more than 15 days, maximum in Hel

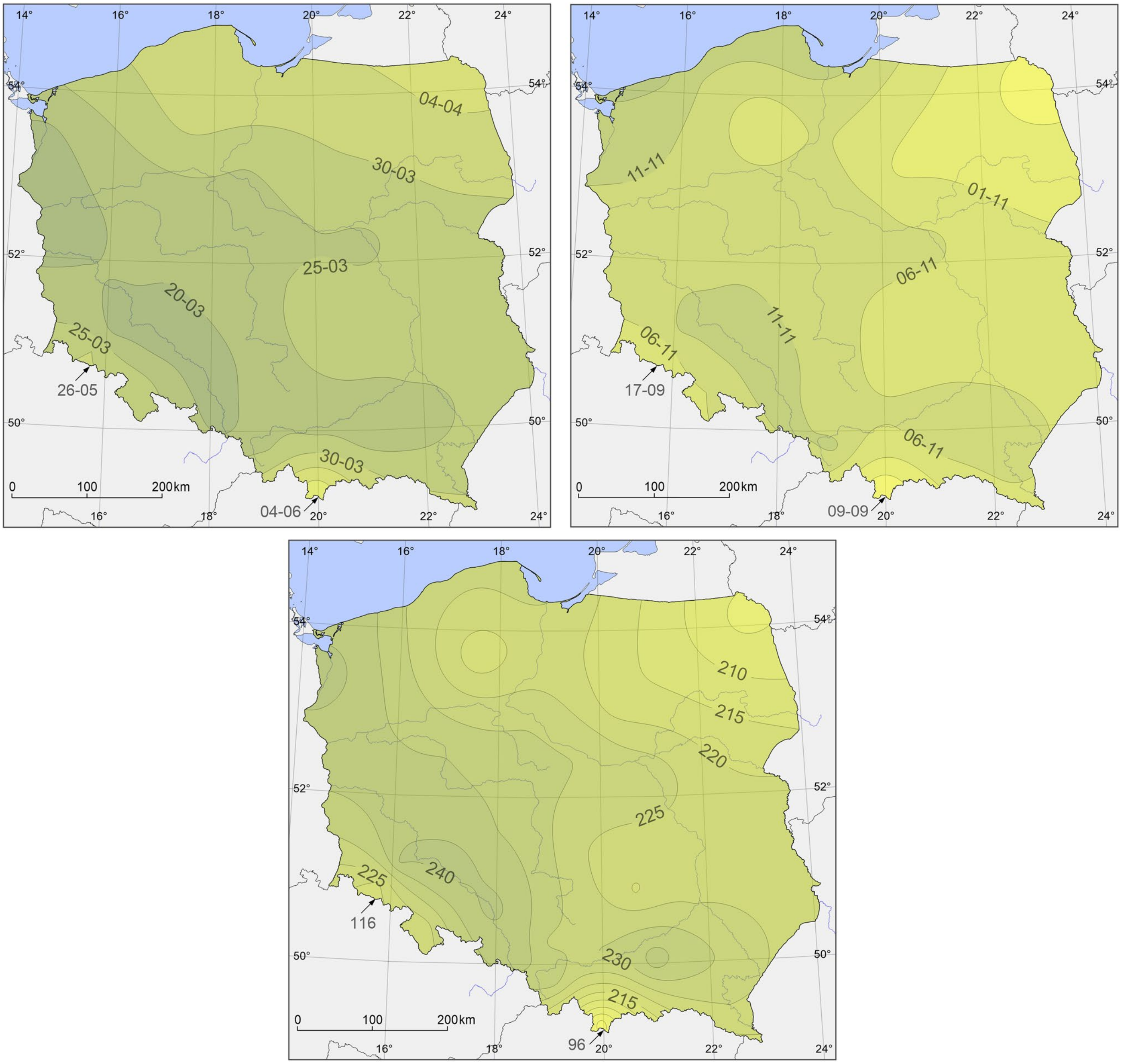

Fig. 2 Average growing season start date (upper right), end date (upper left) and length (bottom) in Poland in the years 1966–2020

16.9 days), and the lowest in central and east Poland and in mountain stations (minimum on Śnieżka 10.9 days). In the latter scenario, the greatest acceleration will be recorded in the western, southwestern, and northern regions of the country (maximum in Szczecin 30.1 days) and the smallest in the east of the country and in the mountain stations (minimum on Śnieżka 21.5 days). The above data suggest that higher spatial variability of the forecasted changes will occur in the case of scenario RCP8.5. The greatest differences between changes in RCP4.5 and RCP8.5 were determined in the western and southwestern regions of Poland. Differences in the magnitude of changes between RCP4.5 and RCP8.5 are particularly evident in the long-term perspective, averaging 15 days (for comparison, in the short-term perspective, they average only 1.4 days).

The average start date of the growing season in Poland in subsequent decades will vary from 6 March in the long term in RCP8.5 to 26 March in the short term in RCP4.5 according to the median (Fig. 3). In all projections, the season's start is projected to progress from the southwest toward the northeast. It will be recorded the latest in mountain areas. As mentioned above, the greatest changes are projected for the long-term perspective in RCP8.5. In that case, the start of the growing season is projected to be

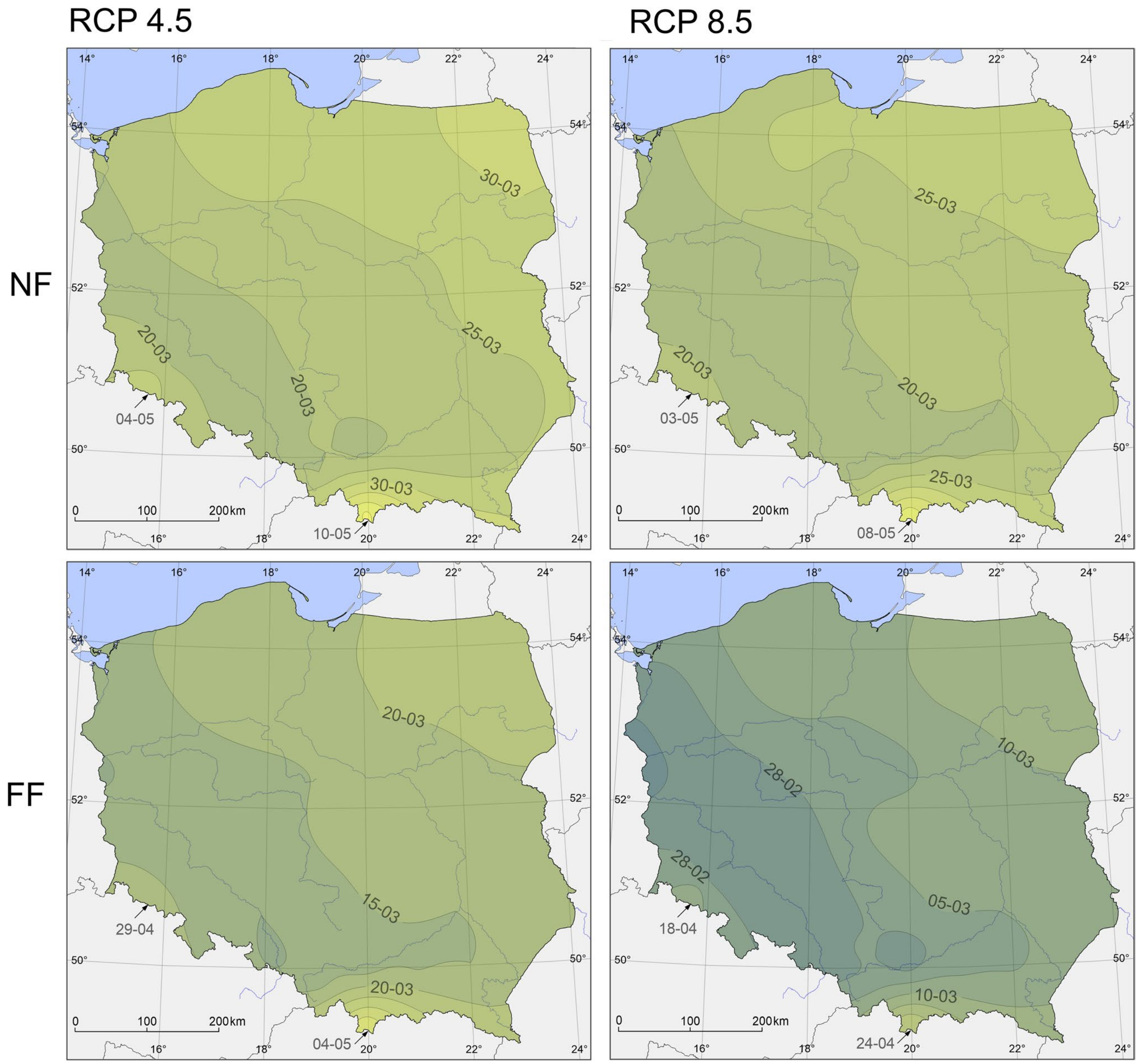

Fig. 3 Start of the growing season in the near (top row) and far (bottom row) future in RCP4.5 (left column) and RCP8.5 (right column)

recorded at the beginning of the third decade of February in the west of the country and at the turn of the first and second decade of March in north-east Poland. In the mountains, projections point to the second decade of April on Śnieżka and the third on Kasprowy Wierch.

In subsequent years of the 21st century, changes in the end date of the growing season will also be observed (Fig. 4). In the analyzed time perspectives and climate change scenarios, the date will be recorded somewhat later (Table 1). In the short term, the average end date of the season in Poland will occur later than in the reference period by approximately 8 days in RCP4.5 and 10 days in RCP8.5. In the case of both scenarios of greenhouse gas emissions, they are projected to be the most intensive in the northern and north-western parts of the country and weakest in the south-eastern regions of the country and in the mountains. In RCP4.5, the greatest changes are projected to be observed in Hel (12.6 days) and Świnoujście (12.1 days) and the smallest in Zakopane (6.1 days) and Lesko (6.2 days). A similar spatial variability is projected to be recorded in RCP8.5, although the changes are projected to be more intensive, i.e., in Świnoujście 13.4 days, and in Lesko 8.4 days. The above data show greater spatial variability of the forecasted changes in the case of scenario RCP4.5.

Changes in the end date of the growing season will proceed more intensively in the long-term perspective. On

Table 1 Changes in the date of start and end of the growing season and its duration in relation to the reference period 1971–2000

Stations	Start date of the growing season				End date of the growing season				Duration of the growing season			
	NF4.5	NF8.5	FF4.5	FF8.5	NF4.5	NF8.5	FF4.5	FF8.5	NF4.5	NF8.5	FF4.5	FF8.5
Białystok	−5,2	−7,7	−12,9	−22,1	7,7	9,2	11,6	24,3	13,0	16,9	24,5	46,4
Bielsko-Biała	−5,8	−7,8	−12,9	−25,7	7,3	9,3	13,3	28,0	13,1	17,1	26,2	53,7
Chojnice	−5,2	−7,7	−13,4	−24,0	8,9	9,8	13,3	29,2	14,0	17,5	26,7	53,2
Gorzów Wielkopolski	−5,3	−7,0	−12,7	−27,7	8,8	10,5	14,7	31,9	14,1	17,5	27,3	59,7
Hel	−8,2	−10,0	−16,9	−27,9	12,6	13,4	19,4	36,5	20,8	23,4	36,3	64,4
Jelenia Góra	−5,8	−8,7	−14,2	−26,0	7,9	9,3	13,5	30,0	13,7	18,0	27,6	56,0
Kalisz	−5,2	−7,2	−12,4	−25,7	8,1	9,7	13,7	29,4	13,2	16,8	26,0	55,0
Kasprowy Wierch	−7,1	−8,9	−13,2	−23,6	7,8	11,3	14,7	24,1	14,9	20,2	27,8	47,7
Katowice	−5,1	−7,0	−12,2	−25,0	7,3	9,0	12,4	27,7	12,4	16,0	24,5	52,7
Kielce	−5,2	−7,5	−12,8	−23,4	7,1	8,6	11,2	25,8	12,3	16,0	23,9	49,1
Kłodzko	−6,0	−8,3	−13,6	−26,3	7,5	8,9	13,2	29,5	13,6	17,2	26,8	55,8
Kołobrzeg	−7,2	−9,2	−14,7	−26,9	12,1	12,9	19,0	36,7	19,3	22,1	33,7	63,6
Koszalin	−6,2	−8,7	−14,7	−27,2	10,3	11,3	16,0	32,1	16,5	20,0	30,7	59,2
Kraków	−5,2	−7,1	−12,6	−26,5	7,8	9,5	13,1	28,6	13,0	16,6	25,7	55,0
Legnica	−4,9	−6,7	−12,5	−27,4	8,4	9,9	14,2	30,7	13,3	16,6	26,7	58,1
Lesko	−5,3	−7,5	−12,6	−22,6	6,2	8,4	11,0	23,7	11,4	15,9	23,6	46,3
Leszno	−5,1	−6,9	−12,6	−27,4	8,3	9,9	14,1	31,1	13,5	16,7	26,7	58,5
Lublin	−5,4	−7,3	−12,1	−21,6	7,4	8,7	11,3	24,7	12,8	16,0	23,4	46,3
Łeba	−7,3	−9,8	−15,9	−29,4	11,7	12,1	17,6	33,5	19,0	21,9	33,5	63,0
Łódź	−5,1	−7,5	−12,4	−22,6	8,0	9,0	12,1	26,7	13,1	16,5	24,5	49,3
Mława	−5,1	−7,6	−13,3	−22,9	8,2	9,5	12,4	26,9	13,3	17,0	25,6	49,8
Olsztyn	−5,3	−7,9	−13,7	−23,9	8,6	9,9	13,0	27,8	13,9	17,8	26,6	51,7
Opole	−5,0	−6,9	−12,6	−27,2	7,7	9,6	13,8	29,6	12,7	16,5	26,4	56,8
Płock	−5,0	−7,3	−12,4	−24,4	8,4	9,7	12,8	28,8	13,4	17,1	25,2	53,2
Poznań	−5,0	−7,1	−12,4	−26,3	8,6	9,8	14,0	30,5	13,5	17,0	26,4	56,9
Racibórz	−5,2	−7,0	−12,7	−26,9	7,8	9,6	13,7	28,9	13,0	16,6	26,4	55,9
Rzeszów	−5,8	−7,5	−12,5	−23,4	7,2	8,5	11,8	25,5	13,0	16,0	24,3	48,9
Sandomierz	−5,3	−7,2	−12,0	−22,6	7,5	8,5	11,2	25,3	12,8	15,7	23,2	48,0
Siedlce	−5,0	−7,5	−12,4	−22,0	7,5	9,0	11,5	25,0	12,4	16,5	23,9	47,0
Słubice	−5,3	−6,8	−13,3	−29,8	9,5	10,8	15,7	34,2	14,7	17,6	29,0	64,0
Sulejów	−5,0	−7,2	−12,2	−22,9	7,9	8,8	11,8	26,5	12,9	16,0	23,9	49,4
Suwałki	−5,7	−8,1	−14,0	−23,3	8,4	9,8	12,8	25,7	14,1	17,9	26,8	49,1
Szczecin	−5,8	−7,9	−13,5	−30,1	10,1	11,2	16,2	34,2	15,9	19,1	29,8	64,2
Śnieżka	−5,2	−6,9	−10,9	−21,5	7,8	9,6	13,4	22,0	13,0	16,5	24,4	43,5
Świnoujście	−6,9	−8,9	−14,2	−26,4	12,1	12,7	19,4	38,0	18,9	21,5	33,6	64,4
Tarnów	−5,3	−7,3	−12,4	−24,0	7,3	8,8	12,1	25,9	12,6	16,1	24,5	49,9
Terespol	−5,2	−7,3	−12,1	−21,8	7,4	8,9	11,2	24,8	12,6	16,1	23,4	46,6
Toruń	−5,2	−7,6	−13,0	−24,9	8,6	9,7	13,0	29,6	13,8	17,3	26,0	54,5
Warszawa	−5,1	−7,2	−12,2	−22,7	8,1	8,9	11,8	27,0	13,2	16,1	24,0	49,7
Wrocław	−5,3	−7,0	−12,7	−28,0	8,2	9,9	14,1	31,0	13,5	16,8	26,7	59,0
Zakopane	−4,4	−7,2	−11,9	−25,7	6,1	9,0	11,9	23,1	10,5	16,3	23,8	48,8
Zielona Góra	−5,2	−6,8	−12,3	−26,9	8,4	9,9	13,9	30,6	13,6	16,7	26,2	57,5
Average	−6	−8	−13	−25	8	10	14	29	14	17	27	54

average, in Poland, at the end of the 21st century, the growing season is projected to end 14 days later in the case of RCP4.5 and as many as 29 days later for RCP8.5. According to the forecasts, the spatial variability of changes in the growing season end date will be almost twice as high in RCP8.5. Like in the short-term perspective, the most intensive changes will occur in north and north-west Poland. They will be considerably weaker in the eastern regions of

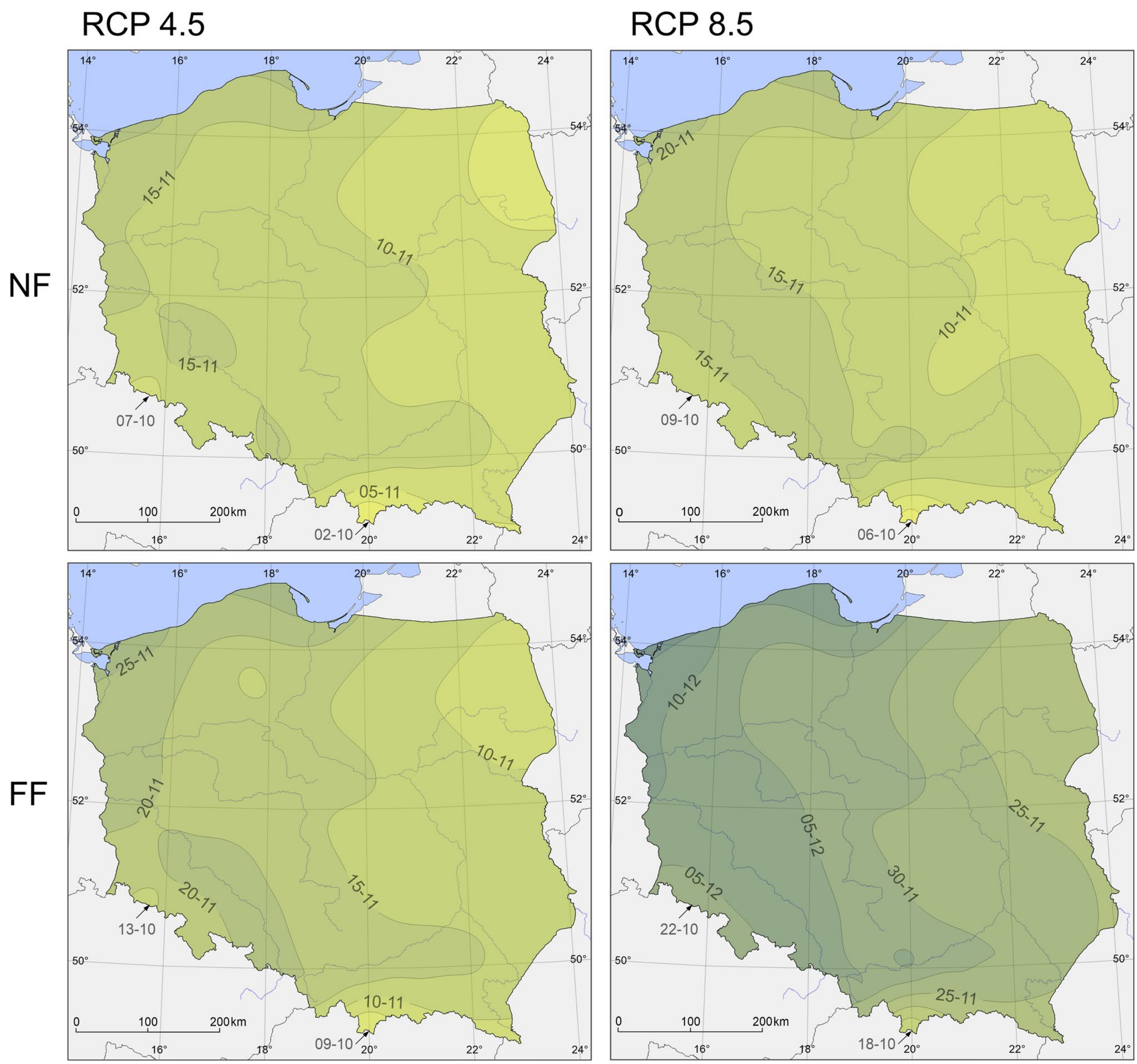

Fig. 4 End of the growing season in the near (top row) and far (bottom row) future in RCP4.5 (left column) and RCP8.5 (right column)

the country and in the mountains. In RCP4.5, the greatest changes will be recorded in Hel and Świnoujście (19.4 days), and the smallest in Lesko (11.0 days). In RCP8.5, the changes will be substantially more intensive. They are forecasted at a level of 38.0 days in Świnoujście and 22.0 days in Śnieżka.

The growing season end in the 21st century will progress from the north-east and mountain areas toward the southwest and north-west of the country (Fig. 4). The average growing season end date in Poland will vary from 10 November in RCP4.5 in the short term to 1 December in RCP8.5 in the long term. At the end of the 21st century, the growing season end in north-east and east Poland will be recorded in the 3rd decade of November. The end of the season will occur considerably later in the west and north of the country, and the latest in the west coast, only in the second decade of December. In the mountains, the growing season end date will be recorded in the second decade of October on Śnieżka and in the third decade on Kasprowy Wierch.

Growing season duration in near and far future

The consequence of an earlier start and increasingly later end of the growing season is projected to be an increase in its duration (Fig. 5, Table 1). In the short-term perspective, the growing season is projected to last longer by an average

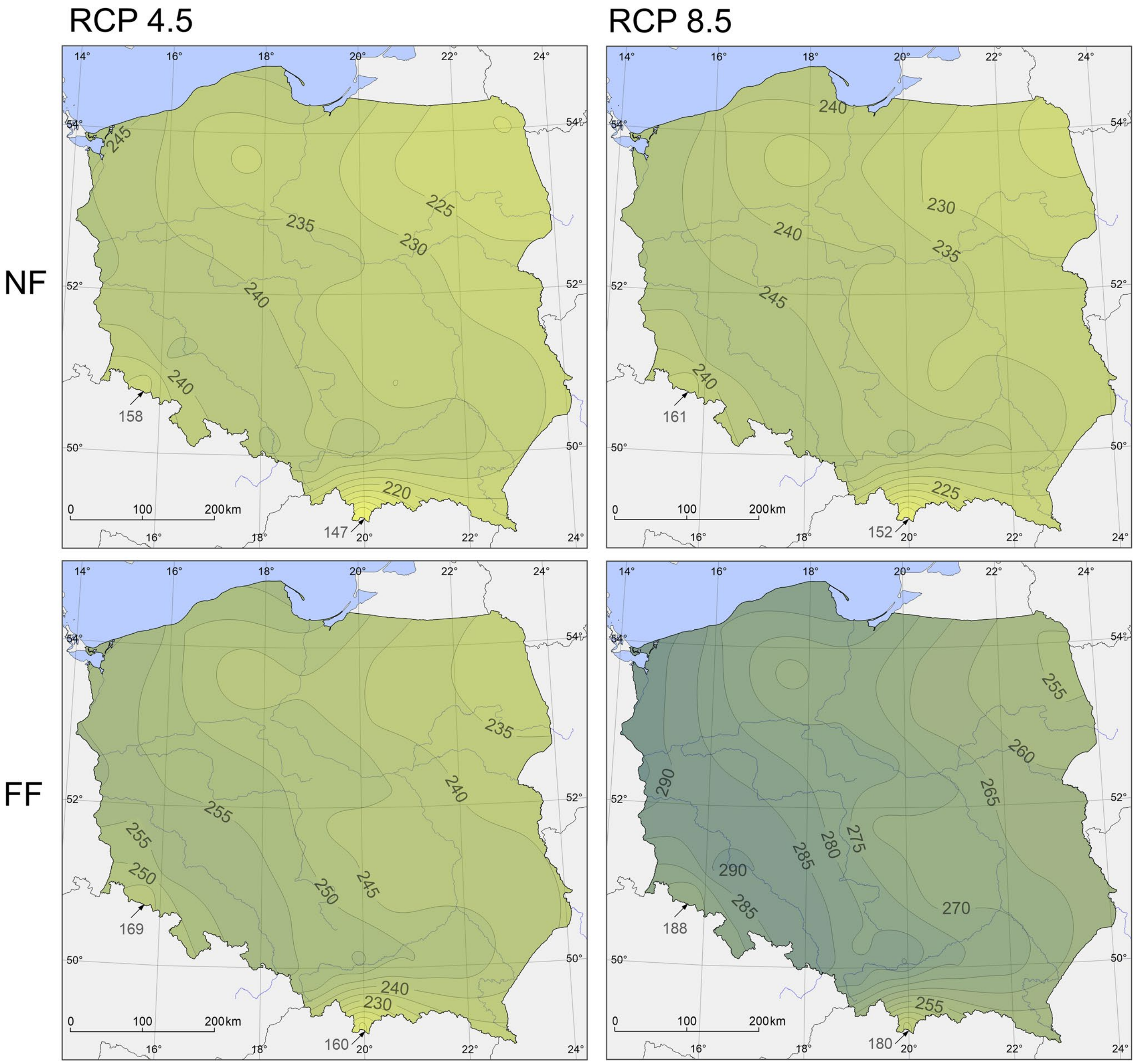

Fig. 5 The duration of the growing season in the near (top row) and far (bottom row) future in RCP4.5 (left column) and RCP8.5 (right column)

of 14 days in RCP4.5 and 17 days in RCP8.5. In both scenarios, the greatest increase in the season duration will be recorded in north and north-west Poland, and the smallest in north-east Poland and in the mountains. In RCP4.5, changes in the season duration will vary from 10.5 days in Zakopane to 20.8 days in Hel, and in RCP8.5, from 15.7 days in Sandomierz to 23.4 days in Hel. Greater spatial variability of an increase in the season duration is determined in RCP4.5 than in RCP8.5.

In the long-term perspective, changes in the growing season duration slightly differed in their spatial distribution in RCP4.5 and RCP8.5 (Fig. 5). In the analyzed time perspective, the average growing season duration will increase by 27 days in RCP4.5, and in RCP8.5 by 54 days. In the high-end greenhouse gas emission scenario, next to the northern regions, the western regions of Poland showed a considerable increase. The level of the changes decreased eastwards and in the mountains. In the first scenario, the range of changes was from 23.2 days in Sandomierz to 36.3 days in Hel, and in the second one, from 43.5 days on Śnieżka to 64.4 days in Hel and Świnoujście. According to the above data, higher spatial variability of an increase in growing season duration will be recorded in RCP8.5.

Illustrating the variability of the projected changes in the applied climatic models involved the calculation of the average spatial changes in the growing season start and end date as well as its duration and their presentation in the form of box plots (Fig. 6). In the case of start and end date as well as the duration of the growing season, higher variability of changes was projected on average in the short-term perspective. The greatest range was observed for the projections of growing season duration in the long-term perspective in RCP4.5, reaching approximately 22 days. Relatively high model spread was determined for the projections of the season end date and its duration in the short term in RCP4.5. The most coherent calculation results were recorded in the historical period, with a variability of only several days.

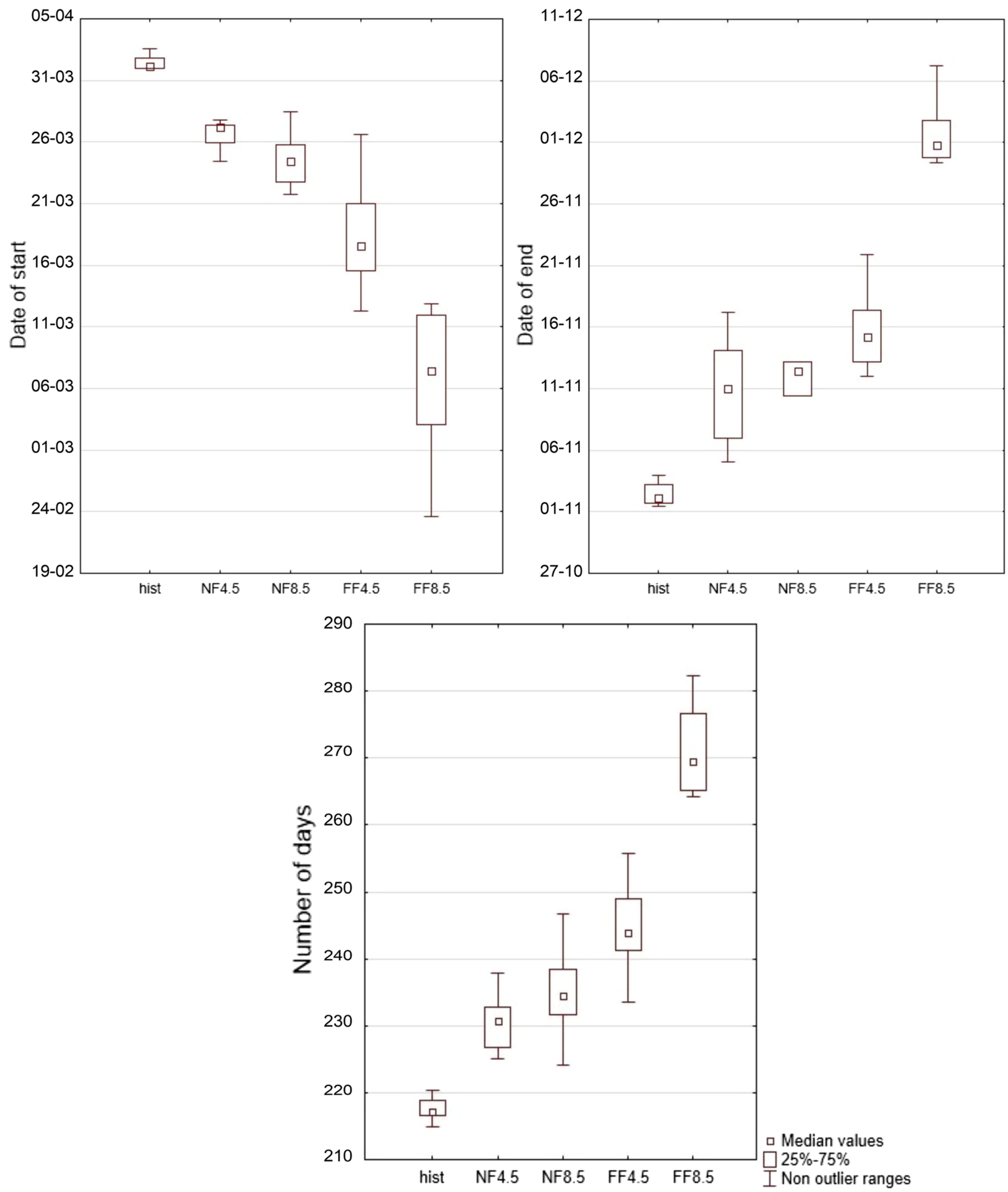

Fig. 6 Box plots showing areal mean historical variability and projected changes in the growing season start and end date as well as its duration

Discussion

The study found an increase in the length of the growing season by an average of 4.8 days/10 years between 1966 and 2020.

The largest increase in the length of the growing season was recorded in northern Poland. The average start date in Poland tended to go back faster in the study period, while the end of the growing season occurred gradually later, at a slower rate, causing the extension of the growing season length. The cause of the increase showed spatial variability—stations in the northwest and central-east Poland and in the mountains were characterized by a greater shift of growing season start than the end, and the situation was the opposite over the remaining area. Earlier research by the authors in Poland points to a stronger contribution of the end delay to its longer duration (Tomczyk and Szyga-Pluta 2019). In the period 1972–2020 in Central Europe, the growing season was prolonged, although changes in the analyzed stations occurred unevenly and resulted from different reasons—a greater shift of the end date in the north or earlier start date in the south of the study area (Szyga-Pluta et al. 2022; Szyga-Pluta et al. 2023). Such variability also occurred in Finland: in the north, the end was delayed, the start was early in the centre, and on the southwest coast, the shift of the start and end of growing season was the same (Irannezhad and Kløve 2015). In Estonia, the prolongation of the growing season results in both its early start and later end, and in the 50 year period (1965–2014), the growing season was prolonged by approximately 2 weeks, primarily due to earlier spring—it started on average 17 days earlier in the south and 10 days earlier in the north of the country (Tarand et al. 2013; Saue and Käremaa 2015). Song et al. (2010) determined prolongation of growing season primarily resulted from 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 date and end date. Based on phenological changes in the north and central Europe, greater changes were observed in spring (Menzel 2000).

The comparison of the rate of increase in the discussed parameters (per 10 years) in the period 1966–2020 and in the short- and long-term perspective evidently shows an increase in the rate of the projected changes.

Projections of changes in the growing season start in both scenarios of greenhouse gas emissions point to the strengthening of the trend of the shift in the date to an increasingly earlier one. On average, in Poland, in the short term, the start date is projected to be recorded approximately 6 days earlier in the case of RCP4.5, and approximately 8 days earlier for RCP8.5, i.e., 3.4 days and 5.4 days earlier than in the years 1966–2020, respectively. Both scenarios showed relatively low spatial variability of deviations from average values from the reference period, reaching 3.8 days for RCP4.5 and 3.3 days for RCP8.5.

In the long-term perspective, changes in the growing season start will occur considerably more intensively than in the short term. The greatest differences between changes in RCP4.5 and RCP8.5 were recorded in the southern and southwestern regions of Poland. Differences in the magnitude of changes between RCP4.5 and RCP8.5 are particularly evident in the long-term perspective, reaching an average of 15 days (in the short term, an average of only 1.4 days).

In the short-term perspective, the average growing season end date in Poland will occur later than in the reference period by approximately 8 days in RCP4.5 and 10 days in RCP8.5. In the case of both greenhouse gas emission scenarios, the changes will be the most intensive in the northern and north-western regions of the country and the weakest in the south-eastern regions and in the mountains. Changes in the growing season end date will be more intensive in the long term. According to the forecasts, the spatial variability of changes in the growing season end date will be almost twice as high in RCP8.5.

Greater spatial variability of an increase in growing season duration is determined in RCP4.5 than in RCP8.5. Greater spatial variability in an increase in growing season duration will be recorded in RCP8.5.

The obtained results are in accordance with projections obtained by other authors. Average forecasts obtained by Zhou et al. (2018) based on many models show a prolongation and warming of the growing season in northern Eurasia. The prolongation of the growing season in the conditions of warming by 1.5 °C and 2 °C is attributed by the authors to both the earlier start and later end of the season, whereas the latter factor plays the dominant role. Interestingly, the earlier start is of more importance in the case of RCP4.5 than RCP8.5 in terms of growing season prolongation due to an increase in temperature by a further 0.5 °C. Ruosteenoja et al. (2020) predict that in northern Europe in the period 2040–2069 in the scope of RCP4.5, the average duration of thermal summer will increase by approximately 30 days in comparison with the period 1971–2000, and the duration of thermal winter will decrease by 30–60 days. Thermal spring will occur earlier, and autumn later. It is expected that by 2050, the growing season will be prolonged by an average of 16–24 days in the northern and 18–28 days in the southern part of Estonia (Saue and Käremaa 2015). The thermal growing season in the period 2070–2099 will be prolonged in inland areas in Finland by 40–50 days and even more on the southwest coast (Ruosteenoja et al. 2011).

The increase in the length of the growing season implies changes in agriculture. According to the research of Marcinkowski and Piniewski (2018), the projected climate change has significantly affected the potential timing of farming practices, accelerating the occurrence of sowing and harvesting dates. The sowing/harvest rate accelerated over time, reaching 23 days for spring barley and 30 days for maize (set average for the far future with RCP8.5). These results are consistent with studies reporting a longer growing season and faster accumulation of growing degree days (Graczyk and Kundzewicz 2016; Wypych et al. 2017; Szyga-Pluta 2022; Szyga-Pluta et al. 2022).

To sum up, the growing season in Poland is projected to be the shortest in mountain areas and in the north-eastern regions of Poland, where the date of growing season start is the latest and the date of the growing season end is the earliest. Whereas the longest growing season due to the projected earliest start and latest end dates is expected in the southwestern Poland. In the case of the coast, its late end will be of the greatest importance for its duration as a result of the warming effect of the sea in the autumn–winter period. This suggests significant changes in agroclimatic conditions in Poland. For comparison, in the period 1971–2010, the growing season lasted from 200 days in northeast Poland to 237 days in southwest Poland (Tomczyk and Szyga-Pluta 2016). According to calculations by Szwejkowski et al. (2017), the shortest predicted growing seasons can last for the same number of days as currently, and the maximum predicted duration might exceed the current state by almost 4 months.

Conclusions

Research has proven the consolidation of the trend of moving the start date to earlier and earlier. In the distant future, changes in both the beginning and the end of the growing season will occur much more intensively than in the near future. The most intensive changes are forecasted in the long-term perspective in the case of the scenario regarding a high level of greenhouse gas emissions.

The forecasted changes in growing season duration must undoubtedly entail changes in agriculture. For agricultural ecosystems, there is evidence that some crops species and varieties currently grown in a particular area may not be able to adapt quickly enough to the changes. Because different species will react differently, the complex interactions among species will be disrupted, potentially affecting ecosystem services such as pollination and the control of crop pests by natural predators. Plant and animal pests and diseases may spread into areas where they were unknown before, but important knowledge gaps remain in this area (Porter et al. 2014). Moreover, climate change may affect the nutritional properties of some crops. It was found that under conditions of elevated levels of carbon dioxide, the concentrations of minerals in some crops (e.g., wheat, rice and soybeans) can be up to 8% lower than normal. Protein concentrations may also be lower, while carbohydrates are higher (FAO 2015). Detailed guidelines regarding adaptation can be therefore related to changes in production techniques that affect the water balance/demand of crops, efficient use of water and soil resources (EEA 2005), adjusted schedule and selection of crops, and changes in the management of pests/diseases/weeds.

Author's contribution KSP: Conceptualization; data curation; formal analysis; investigation; methodology; project administration; supervision; validation; visualization; writing—original draft. AMT: Conceptualization; data curation; formal analysis; investigation; methodology; project administration; resources; software; supervision; validation; visualization; writing—original draft. MP: Data curation; formal analysis; methodology; software; validation; visualization. MRE: Data curation; formal analysis; methodology; software; validation; visualization.

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Data availability The obtained data can be made available on request of interested parties under the condition of approval of the request by the authors of the article.

Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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