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Climate change from an agricultural perspective

Zmiany klimatu z perspektywy rolnictwa

Abstract. The fact of the global climate system warming is undeniable. Climate changes have been generally observed since the 1990s. The paper examines various meteorological variables influencing plant production to trace how the climatic conditions for agriculture development in Poland are changing with climate warming. This research showed significant differences in agrometeorological characteristics before warming (1961–1990) and during this process (1991–2020). The thermal characteristics crucial for agriculture have changed, impacting the extension of growing and frost-free periods, among other things. Winters are now "milder". An acceleration of the date of the last spring frost was recorded. The most severe change in precipitation is its increase, especially in winter, with snow having an increasingly smaller share of this precipitation.

Keywords: climate change, thermal condition, precipitation, snow cover, growing season

INTRODUCTION

Climatic conditions determine the ability of a given area to develop agriculture, as expressed, among other factors, by the duration of the economic period, the growing season, the period of active plant growth (related to air temperature), and precipitation (water conditions element) [Szwejkowski at al. 2009].

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For plant production needs, two primary periods are distinguished based on average daily air temperatures: the economic period and the growing season. A longer growing season brings many benefits for plant production. It extends optimal agrotechnical periods for cultivating winter plants and expedites those for spring forms. Prolonging the autumn vegetation period is beneficial for sowing winter crops. Favorable temperatures for an extended duration enable timely autumn plant protection treatments against weeds and fungal diseases. Unfortunately, extending the growing season can sometimes have adverse effects. A longer growing season may be associated with increased threats to crop plants, including pests, a rise in crop weeds, an increase in the population of overwintering pests, etc.

The observed variability in plant yields in Poland is mainly caused by periodically occurring unfavorable meteorological factors and the consequent intensification of pest pressure [Wójcik-Gront and Gozdowski 2023]. Adverse weather conditions can significantly diminish the impact of incurred expenses and agrotechnical procedures. These detrimental factors pose a particular threat to plants during winter and early spring. In Poland, many unfavorable climatic and weather factors affect plant production. In winter, severe frosts and winds with insufficient snow cover, prolonged thick snow cover, atmospheric and soil thaws, sudden thaws, and ice cover pose severe threats to plantations. During the growing season, the main hazards to crop plants include long-term and excessive rainfall, atmospheric and soil droughts, frosts, hailstorms, lack of sunlight and heat, storms, and strong winds [Czarnecka et al. 2009].

The potential conditions for agriculture in Poland are relatively favorable due to the high agricultural culture and natural conditions, including climatic conditions shaped by the temperate climate zone. However, climatic conditions are not constant. The transitional, maritime-continental nature of the Polish climate, resulting from Poland's location where continental and oceanic masses often collide, has led to relatively large day-to-day and year-to-year variability in the weather patterns [Krasowicz et al. 2009].

In recent years, Poland's climate pattern has been supplemented by the "greenhouse variable". The unequivocal warming of the global climate system is now evident. In 2011–2020, the Earth's average temperature was 1.09°C higher than that in 1850–1900, which is considered equal to the temperature in pre-industrial times. Each of the last four decades was warmer than its predecessors [IPCC 2021]. Poland is no exception to this trend.

The statement on relatively large day-to-day and year-to-year variability in the weather patterns remains accurate. However, climate changes have been generally observed since the 1990s, altering the "typical season" characteristics. Climate change is also visible in extreme weather phenomena – more frequent and prolonged heat waves, droughts, heavy rainfall, etc. [Falarz 2021]. All of these changes undoubtedly impact the potential climatic conditions for the development of agriculture.

This paper examines various meteorological variables influencing plant production to trace how the climatic conditions for agriculture development in Poland are changing with climate warming. For this purpose, the research period encompasses the period before the visible warming of the Earth's climate (1961–1990) and the subsequent one when an additional 'greenhouse component' was imposed on the climate curves (1991–2020).

MATERIAL AND METHODS

Time series of average, and minimum values of daily air temperature, the daily sum of precipitation, and the daily depth of snow cover for the period of 1961–2020 for 47 meteorological stations (Fig. 1) were used for the research, employing the public database of the Institute of Meteorology and Water Management – the National Research Institute. The primary criteria for selecting stations was the length of the available time series of records. The authors also try to cover the whole territory of Poland possibly uniformly. Mountain and foothill areas were excluded from the analysis since intensive, highly commercial agriculture is not generally carried out in these areas.

Fig. 1. Location of the analyzed meteorological stations

Based on a time series of daily records, the following characteristic describing potential climate conditions for agriculture development was generated:

1. The duration (days) and cut-off dates of the economic period.

The first day means the initial span of at least 7 days with a daily mean temperature Tavg >3°C. The last day is the first autumn day with Tavg <3°C.

2. The duration in (days) and cut-off dates of the growing season.

The first day of the period is determined based on two conditions: (i) it is the initial span of at least 6 days with a daily average temperature Tavg >5°C, and (ii) once the growing season starts, it cannot be interrupted for at least 6 days with Tavg <5°C. The last day of the period is the first autumn day with Tavg <5°C for at least 6 consecutive days.

3. Annual and seasonal (winter DJF (December, January, and February), spring MAM, summer JJA, autumn SON) precipitation totals in (mm).

4. Mean value of snow cover depth for winter DJF in (cm), and number of days with snow cover during every winter in (days).

5. The last freeze day in spring, and the first freeze day in autumn (date). The freeze day is defined in this research as one with Tavg >0°C and a minimum temperature Tmin <0°C.

6. The longest period without precipitation in spring MAM and summer JJA in (days).

To describe temporal changes in analyzed characteristics for every station, the intervals of 1961–1990 and 1991–2020 were compared. To detect existing trends in the time series of meteorological characteristics, the Hydrospect 2.0 software was used [Radziejewski and Kundzewicz 2000]. Trend detection was carried out using tests: parametric i.e., regression [Draper and Smith 1998] and Mann-Kendall non-parametric [Mann 1945, Kendall 1975]. The statistical significance of the trend for every station was determined.

ArcMap software version 10.2.1 was used to illustrate the spatial distribution of some parameters, with interpolation performed using the IDW (inverse-distance weighting) method [see: Burrough and McDonnell 1998]. However, it should be noted that the mountainous areas were excluded from the analyses. As a result, the isolines in these regions were extrapolated by the software. Given that hypsometry and topography play a dominant role in the course of meteorological indicators in mountainous areas, extrapolation values in these regions should be treated with great caution or even considered as potentially erroneous.

RESULTS

Duration and cut-off dates of the economic period

The start and end dates, as well as the duration of the economic period, vary from year to year in Poland, but a significant extension of the economic period has been observed recently. Currently (mean values for the years 1991–2020), the shortest economic period is recorded in the north-east of Poland and is 214 days in Suwałki. It also starts there at the latest, on average, at the end of the second decade of March. Generally, the economic period in the east begins no earlier than March, and its duration increases going south to approximately 242 days in Rzeszów. The economic period has started much earlier in recent years in the remaining areas. While in central Poland, it falls on average at the end of February, field work could begin as early as the beginning of February in the western parts of the country. In central Poland, the duration of the economic period rises to over 250 days, reaching 272 days in Słubice in the west of the outskirts.

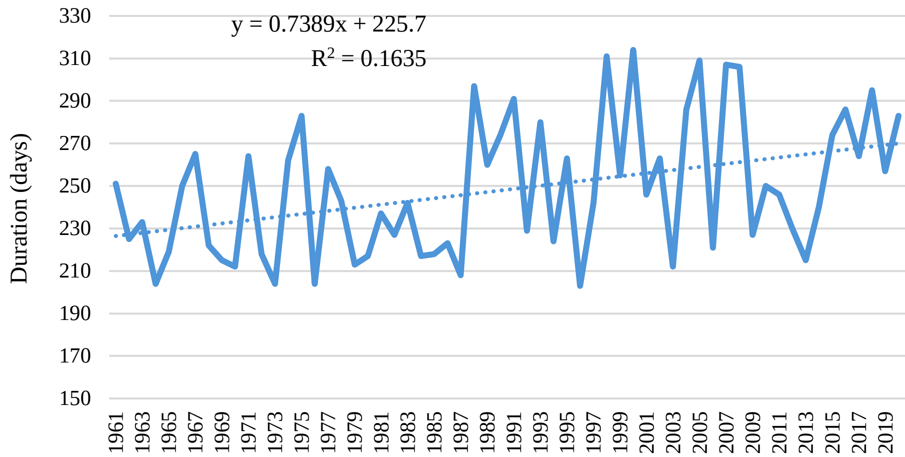

Fig. 2. The duration of the economic period in Kalisz (1961–2020) in days

The given values are about 10–20 days higher than those recorded before 1990 (with the most minor differences in the east of the country). The extension of the economic period is influenced by the earlier arrival of the thermal spring and favorable air temperatures. In contrast, the economic period's end date remains unchanged. Figure 2 illustrates the long-term course of the average duration of the economic period for the randomly selected station Kalisz.

Duration and cut-off dates of the growing season

Today the growing season in Poland is sufficiently long for plant production, lasting over 215 days in most areas. Plant vegetation starts earliest in the southwest and west of the country (in the third decade of March) and extends for approximately 230 days. Conversely, it begins at the latest in the northeastern region (at the beginning or even in the second decade of April) and lasts just over 190 days (Fig. 3b).

From 1961 to 1990, the area where vegetation lasted less than 200 days (northeast Poland) was much larger, about five times. Vegetation in this area began only in the second or third decade of April. The duration of the growing season increased towards the southwest, reaching values of approximately 220 days, with vegetation starting at the beginning of April (Fig. 3a).

a)

b)

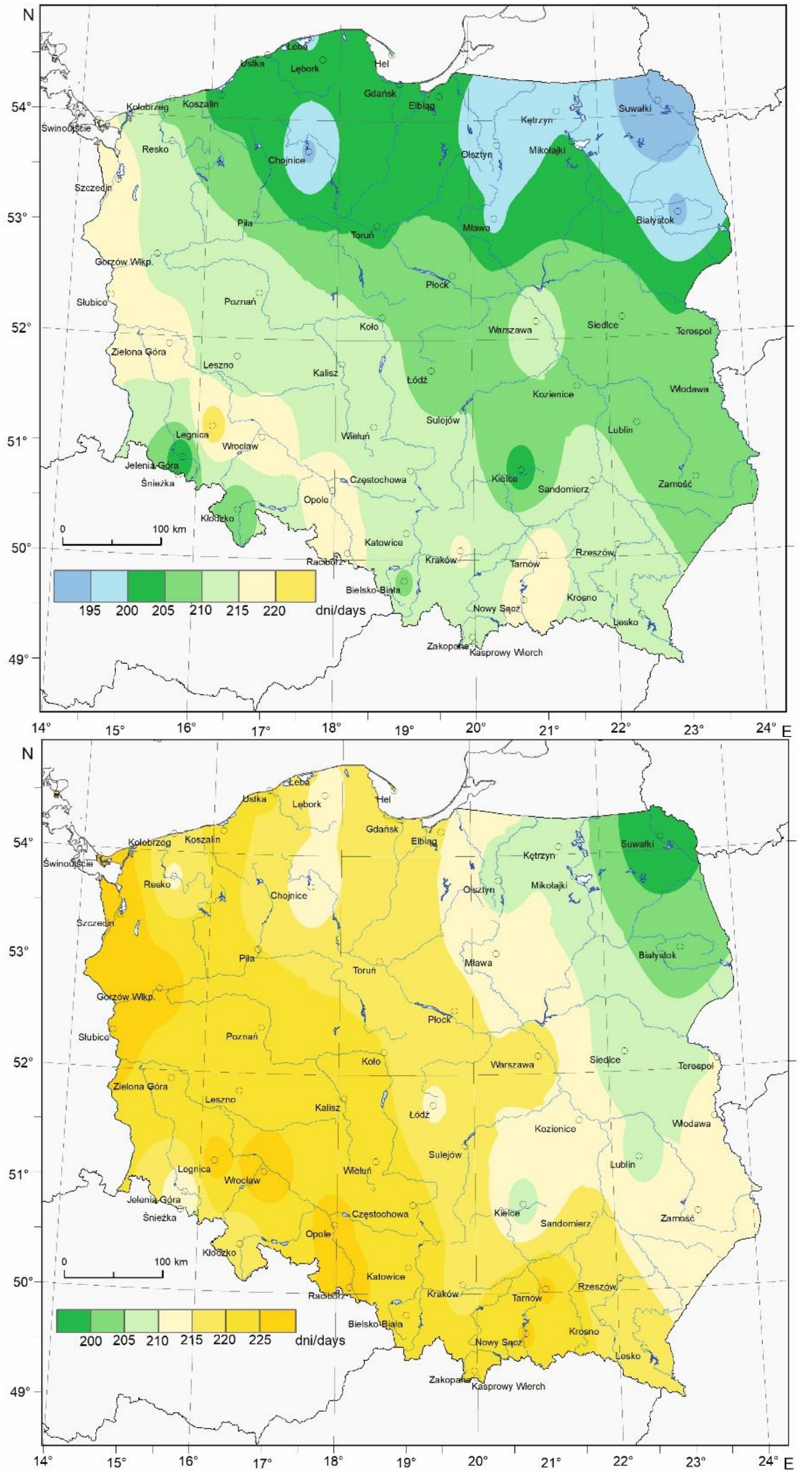

Fig. 3. The duration of the growing seasons in 1961–1990 (a) and 1991–2020 (b) in days

Similar to the economic period, the extension of the growing season is determined by the temperature increases in winter, resulting in an earlier arrival of thermal spring. There were no significant differences between the end of the growing season in both periods examined. These dates remain constant or vary by an average of 2 days.

Precipitations totals

The average annual precipitation totals in Poland is approximately 600 mm per year. The lowest, ranging from 500 mm to 550 mm, is in the lowlands of the central part of the country (Kuyavia, the eastern part of Wielkopolska Region, and western Mazovia). The lowest annual precipitation value between 1991 and 2020 was recorded for Kalisz and amounted to 494 mm. Precipitation in the highlands and lake districts reaches approximately 600–750 mm per year. During the studied period, annual precipitation sums changed slightly in Poland. There is a slight increase in precipitation over most of the country, except southern Poland, specifically the southern edges of the highlands and the foothills. However, these increases are statistically significant only for a few stations. More importantly, in the context of the research topic, seasonal rainfall patterns also change.

The distribution of precipitation throughout the year in Poland is uneven, translating into seasonal variations in precipitation totals. The lowest seasonal sum of precipitation occurs in winter, while the highest is in summer. To illustrate this, Figure 4 displays seasonal rainfall amounts in 1961–2020 in the four seasons for the example of Poznań.

The sum of precipitation during meteorological winter DJF in Poland from 1991 to 2020, based on selected measurement stations (excluding mountain stations), ranged from 69.7 mm in Sandomierz to 170.2 mm in Resko. The lowest seasonal precipitation was recorded in the zone encompassing southern Wielkopolska Region, southern Masovia, and Lublin Province, with levels dropping below 90 mm and further increasing towards the north, northeast, and south. During spring MAM in Poland (1991 to 2020), precipitation totals in the Lowlands ranged from 113.0 mm in Toruń and reached no more than 130 mm. Precipitation generally increases towards the north and the south with altitude, reaching over 200 mm in the foothills (e.g., Bielsko at 255.1 mm). The spatial variation of precipitation during the summer JJA in 1991–2020 ranged from 186.4 mm in Kalisz (the lowlands) to 366.7 mm in Bielsko (the highlands). In autumn SON in Poland during the years 1991–2020, the lowest precipitation sums were recorded in the central zone (e.g., Poznań with 110.2 mm), and they increased towards the north and south (e.g., Łeba with 210.9 mm and Bielsko with 239.6 mm).

Let's compare the current precipitation patterns with those from 1961–1990. There are signs of change undoubtedly related to climate change. Specifically, the winter precipitation pattern has changed. Over the last 60 years, Poland has been divided latitudinally into a northern part (up to the Kalisz–Terespol line), where precipitation increases in winter (with statistically significant trend at several stations), and a southern part, where there are no significant changes in precipitation winter totals (Fig. 5). A similar tendency is observed in summer regarding the direction of changes in precipitation totals and the affected area. However, none of the recorded changes is statistically significant. There is a tendency to increase summer precipitation north of the Kalisz–Terespol line. In spring, precipitation totals change along the east–west axis (up to the Hel–Koło line). In eastern Poland, rainfall has increased over the last 60 years, although not statistically significant, while the west has not recorded any changes in precipitation totals. Autumn is the most stable season regarding the sum of precipitation during the period under study.

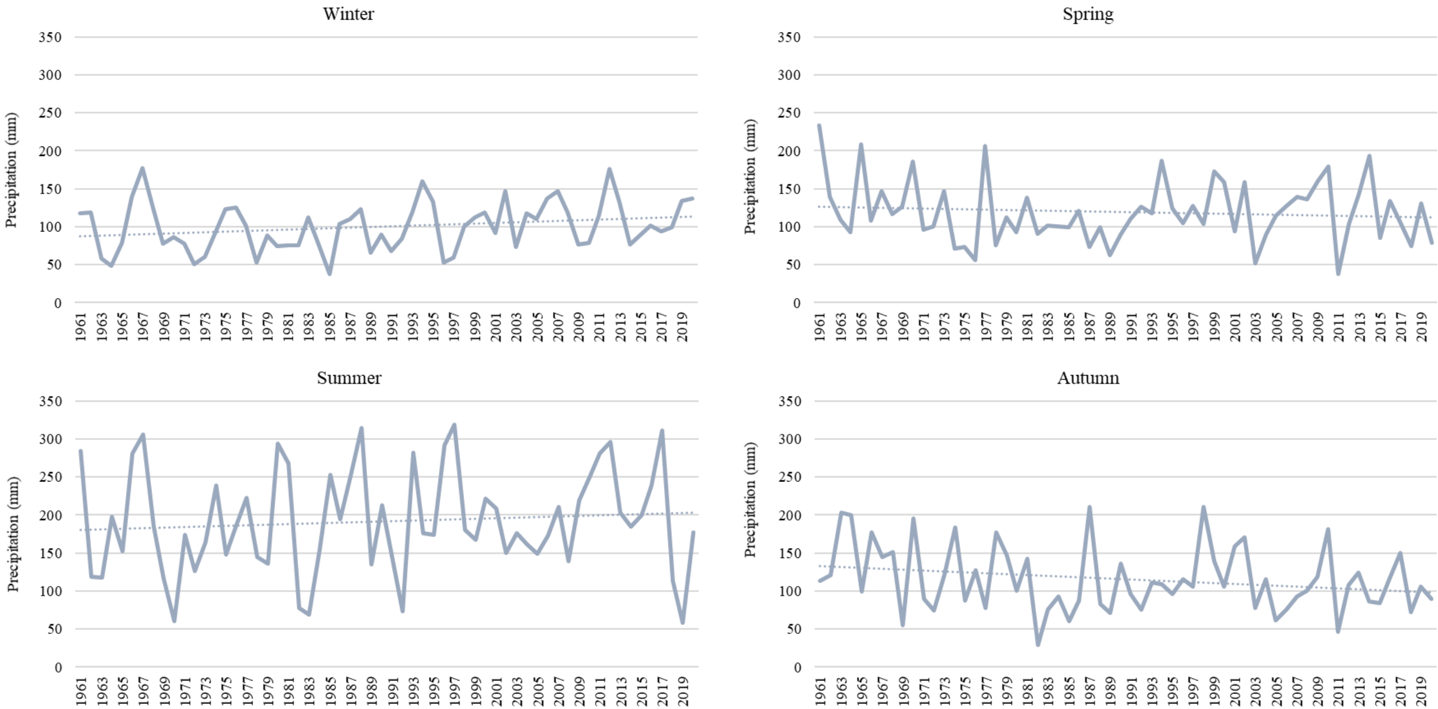

Fig. 4. Seasonal sum of precipitation in Poznań (1961–2020) based on the meteorological division into seasons

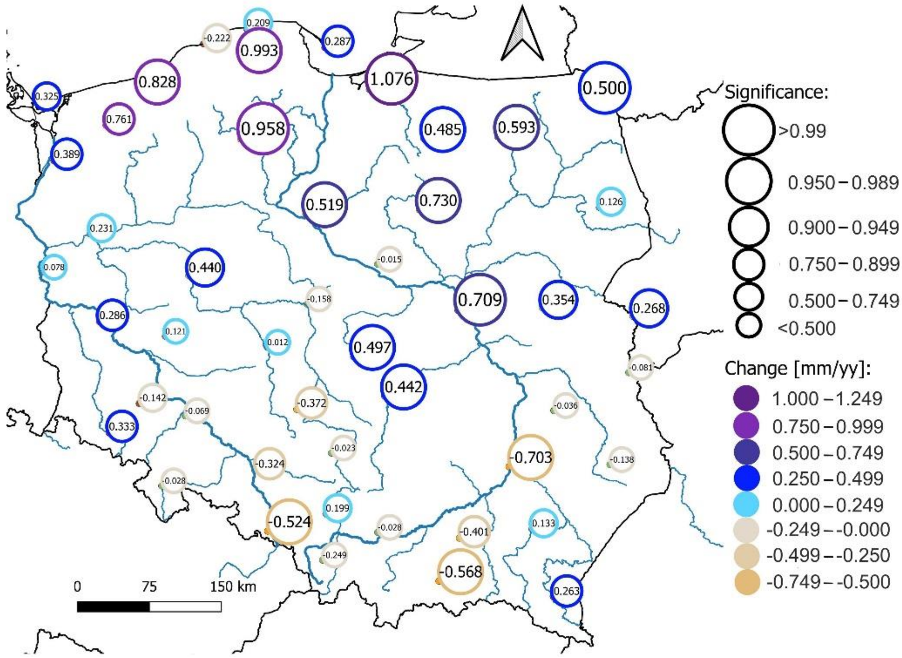

Fig. 5. Precipitation change in winter DJF (1961–2020)

Snow cover

The mean depth of snow cover in winter (DJF) in 1991–2020 in Poland varies from 3.7 cm in Słubice to 13.8 cm in Lesko (except for mountain areas). On average, the lowest depth of snow cover is characteristic for the western part of lowland Poland, while the highest for the eastern part. Comparing the intervals 1961–1990 and 1991–2020, one can conclude that the former was more snowy in terms of mean depth of snow cover (Fig. 6a and 6b). While snowy winters were more common in the earlier period, clusters of almost snowless winters have occurred in the latter. The area with an average thicker snow cover is decreasing. A tendency to reduce snow cover thickness in the analyzed 60-year period was observed for all stations, although it is not statistically significant everywhere. The average reduction in snow cover thickness in 1991–2020 compared to 1961–1990 is 2.5 cm. The snow cover decreases the most in central Poland (a great majority of changes are statistically significant at 0.95).

Along with the reduction in snow cover thickness, the mean number of days with snow cover in winter (DJF) also decreases over time. Snow cover in the period of 1991–2020 lasts, on average, almost two weeks shorter than it did from 1961 to 1990. Although the linear regression of the number of days with cover in all analyzed stations goes down, not all changes are statistically significant at the 0.95 level. The more minor changes are recorded in the southern part of Poland.

a)

b)

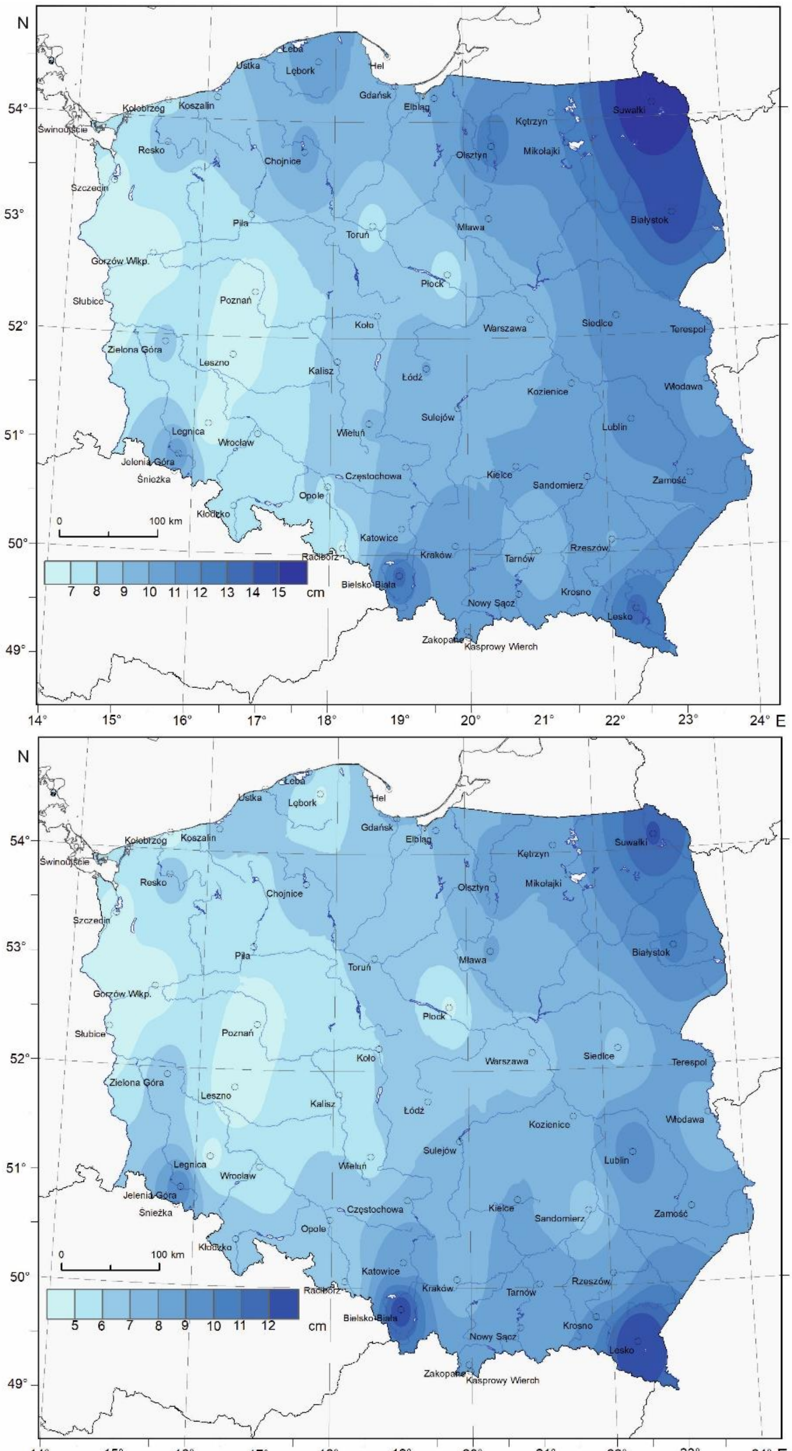

Fig. 6. The snow cover thickness (cm) in winter DJF 1961–1990 (a) and 1991–2020

Freeze days

As for the dates of the last spring and first autumn freeze, it can be said that more significant differences occurred in spring. Thus, the last spring freeze day occurred in Poland in 1991–2020 around April 25 (the average for the country), and it was 5 days earlier than in the years 1961–1990. The western part of the country is characterized by more significant year-by-year variability in the appearance of the last spring frost compared to the eastern regions. Please refer to Figure 7 for box plots illustrating the last spring frost appearance in 1961–1990 vs. 1991–2020 for two stations representing different regions of Poland (Zielona Góra – from the West and Siedlce from the East). Today, the first autumn frost falls on average on October 18th, 2 days later than in 1961–1990. Thus, on average, the frost-free period in Poland has been extended by about a week. If we look at the details, the most significant acceleration of the last spring freeze day, by an average of 11 days, occurs in Zielona Góra. Generally, in the west, the acceleration in the date of the last spring frost is greater (about 7 days or more), while in the east it is only 2 days or less. At two stations – Kielce and Terespol, there was a delay in the considered date (on average less than 1 day). For most stations in the west, the trend detection in the time series of the last spring frost date showed a statistically significant trend indicating its earlier appearance.

Dry periods

In Poland, the onset of atmospheric droughts most often occurs in spring and summer. They are often accompanied by high temperatures that lead to a decrease in relative air humidity. In spring, the most extended uninterrupted periods without precipitation last from 8 to 14 days, with an average of 11.8 days for Poland. Slightly shorter dry periods last in summer. In the summer, they last 8 to 12 days, with an average of 10.4 days for Poland. Both in spring and summer, the average number of days without precipitation did not change during the period under study. Nevertheless, the area of Poland is characterized by very high spatial and temporal variability of rainfall sums and the length of days with and without rainfall. Therefore, deviations from the average value are considerable in individual years. The record-long dry period in spring – 37 days – took place in Kalisz in 2009, while in summer a record – 42 days – was recorded in Świnoujście in 1994.

DISCUSSION AND CONCLUSIONS

Global warming has become a fact at the end of the 20th century, especially since the 1990s. Changes in other climate parameters accompany the undeniable increase in average temperatures on Earth. The amounts, types, and distribution of precipitation are changing, but various extreme events are also occurring with a previously unknown frequency. Overall, climate change cannot go unnoticed in its impact on other non-climatic elements of the geographical environment, humans, and their economy. Agriculture seems to take center stage here as it closely relates to the environment. Despite the progressive development of mechanization, techniques, and technology in agriculture, which help mitigate the negative impacts of climate change, natural conditions, including climatic conditions, still determine the suitability of a given area for the development of agriculture.

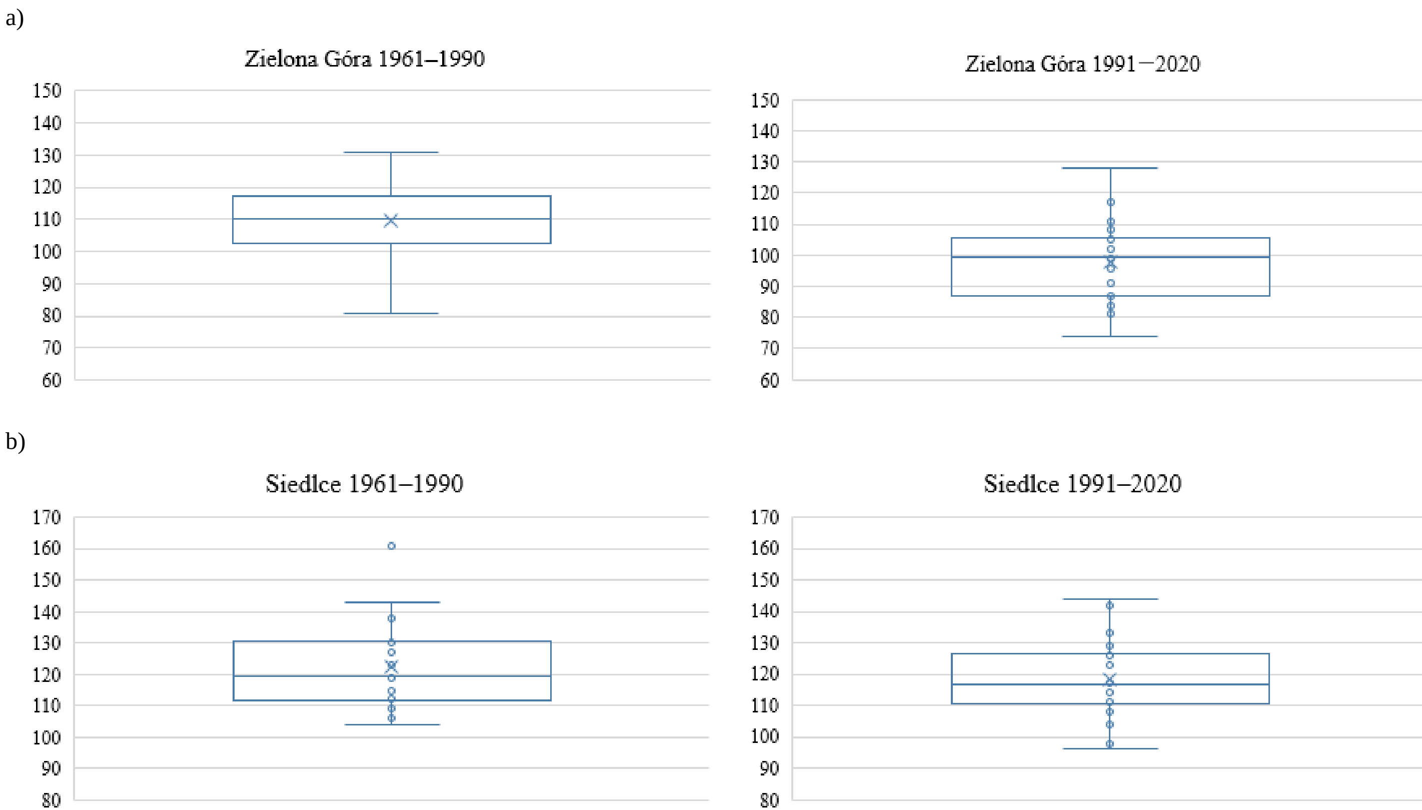

Fig. 7. Box plots illustrating the last spring frost appearance – as a day number in a year – in the periods 1961–1990 vs. 1991–2020 for Zielona Góra (a) and Siedlce (b)

Due to its location in the transitional temperate climate zone, Poland is characterized by high weather variability from day to day, season to season, or between years. This variability is reflected in the cut-off dates and duration of economic and growing seasons, the occurrence of the last spring frosts, etc. The above has been compounded by climate change since the late 1990s.

The primary identifiers of plant production capability seem to be the economic period and the growing season. Both of these periods in Poland are generally long enough for plant production. The economic and growing seasons are the shortest in the north-east and increase towards the west and south-west. Nowadays, both periods last longer (the economic period by about 10-20 days, and the growing season on average by about/over 20 days) than in the period of 1961–1990. In 1991–2020, the beginning of plant vegetation in the southwest and west of the country starts in the third decade of March and progresses across the country, reaching the northeastern corners in the first or second decade of April. The extension of the economic and vegetation periods is determined by the increase in winter temperatures and, thus, the earlier arrival of thermal spring. The end dates of both periods have stayed the same over time. Other researchers also mention the acceleration and lengthening of vegetation in Poland [Nieróbca et al. 2013, Chojnacka-Ożga and Ożga 2018]. Undoubtedly, the extension of the economic and growing seasons potentially benefits plant production, for example, due to the extension of optimal agrotechnical periods.

The duration of the economic and growing season is closely tied to air temperatures. Precipitation is as essential as temperatures for agriculture. The most beneficial conditions for agriculture involve regular and moderate rainfall. Plants' water demand changes during the growing season. Therefore, the distribution of rainfall in individual seasons is of great importance in agriculture. In Poland, the distribution of precipitation throughout the year is uneven, with the vast majority of rain falling in summer. Crop plants typically rely on post-winter water reserves until the end of April or even mid-May. Subsequently, plants' growth, development, and yield depend on the amount of rainfall. In light of this research, this statement may soon be verified.

The total annual precipitation in Poland is slightly increasing. However, at most, there is a certain tendency to increase annual totals, as statistical significance was found only for a few stations. If we analyze individual seasons, the greatest changes occur in winter. Over the last 60 years, there have been statistically significant increases of 0.95 and more in the north and the lowlands. In a similar area, precipitation also increases in summer, but these changes are not statistically significant. In spring, there is only an increasing tendency in precipitation in the west of the country, while in autumn it remains almost unchanged. Even if we accept these as small, statistically insignificant increases, it still seems to be a positive signal for agriculture. Unfortunately, this upward trend in precipitation is overshadowed by a change in the proportion of precipitation types in winter. Although a significant increase in precipitation was observed in winter, this is not accompanied by an increase in the thickness and duration of the snow cover. The snow cover is decreasing, which means the proportion of rainfall to snow also changes in winter in favor of rain. As a result, water from the snow cover is no longer stored and released to plants during the spring thaw but is released into the environment more quickly. This may cause spring drought to develop.

As to the snow cover, its variability over many years and during the winter season has been discussed by many authors [Falarz 2004, Tomczyk et al. 2021]. Generally, the thickness and duration of snow cover increase from west to east, corresponding to the growth of continental features of Poland's transitional climate. In the west, the snow cover remained in the past and currently persists for much shorter than in the east, where conditions favour accumulation and strive during harsher winters. With the warming climate, there is a tendency to reduce the thickness and duration of snow cover. Comparing the analysis periods of 1961–1990 and 1991–2020, it can be concluded that in the last 30 years, approximately 3 centimeters of cover has disappeared, and it remains 2 weeks shorter than years ago. Although these changes are not statistically significant in the entire area, the most substantial snow cover reduction occurs in the central lowlands [also e.g. Wibig and Jędruszkiewicz 2023].

Nowadays, clusters of almost snowless winters are becoming more and more common. This undoubtedly has an adverse effect on the survival of plants in winter. Even though we observe higher temperatures than before 1990, and it might seem that snow cover is no longer necessary for plants to survive since they no longer need protection against frost, the absence of snow cover can have disastrous consequences for plants in spring, particularly in terms of water resources. The accumulative function of the snow cover as a water reservoir is just as crucial as its protective function against frost.

The threat to crop plants related to low temperatures does not end at the end of winter; it also occurs in spring and autumn and is associated with the occurrence of frost (freeze days). Frosts have a significant impact on plants' initial growth. The greater the threat, the later the frosts occur in spring, and the earlier they appear in autumn. However, depending on the species and variety, crop plants show different sensitivities to minimum temperatures. Currently, the last spring frost occurs in Poland in the third decade of April, about 5 days earlier than in 1961–1990. In turn, the first autumn frost falls at the end of the second decade of October, 2 days later than for 1961–1990. Thus, on average, the frost-free period in Poland has been extended by about a week. Similar reports, either on the acceleration of the last spring frost date or the extension of the frost-free period, also come from other Polish authors [Dragańska et al. 2004, Tomczyk et al. 2015]. This might seem to be a particular benefit for plants and agricultural production. Still, it must be taken into account that in parallel with the acceleration of the date of the last spring frost also accelerates the vegetation period (even greater), which means that the date of the last spring frost may find the plants at the same stage of vegetation (or even later) as in the previous period 1961–1990. Therefore, analyzing the threat from this point vision, one could conclude that it does not change over time. It is suggested [Graczyk and Szwed 2020] that to better assess the risk of losses related to exceptionally late and/or strong frosts, the date of their last occurrence should be referenced to the day of the growing season instead of the day number in a year.

In spring and summer, a significant threat to crop plants arises from the mere prolonged periods without precipitation. During summer, increasing evapotranspiration rates due to rising atmospheric temperatures occur. This, in turn, intensifies existing drought conditions that initially developed from rainfall deficits [Hänsel et al. 2019]. This threat intensifies as the rainless period continues. The occurrence of sufficient rainfall immediately before and during the critical period for a given plant species is very important. The greatest sensitivity to lack of water occurs in various plants (depending on the crop type) from May to mid-August.

In light of the results obtained, it can be stated that in spring and summer, the average period without precipitation did not change in the analyzed period of 1961–2020. This result may be influenced by the authors' choice of the "dryness" index dividing the growing season into seasons. Although other authors report the occurrence of rainless periods of similar lengths to those found in this study [e.g., Radzka 2014], it can be assumed that more extended periods, or even significant changes in time, may occur if the growing season as a whole is analyzed.

To sum up, the research presented in this paper focused on agrometeorological indicators characterizing the conditions on which plant cultivation is dependent mainly. In light of this research, it can be concluded that with climate warming, primarily, the thermal characteristics crucial for agriculture have changed, impacting the extension of growing and frost-free period, among other things. Winters are now more "mild". An acceleration of the date of the last spring frost was recorded. The most severe change in precipitation is its increase, especially in winter, with snow having an increasingly smaller share in this precipitation. period. All this leads to the final conclusion that Poland belongs to the countries for which climate change has so far been favorable for agricultural production. According to the IPCC [2021], by the end of the 21st century, global warming will exceed 1.5–2 degrees Celsius unless humanity unprecedentedly reduces emissions of carbon dioxide and other greenhouse gases. We do not know the full consequences. Therefore, climate protection is currently one of the world's most crucial environmental, social, and economic challenges.

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