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ORIGINAL PAPER

# The effect of macro-scale circulation types on the length of the growing season in Poland

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## Abstract
The main objective of the article was to determine the impact of macro-scale circulation types on the beginning and end of the growing season in Poland in 1966–2015. The data concerning average daily air temperature for 30 stations from the period of 1966–2015 were used. Data were obtained from the databases of the Institute of Meteorology and Water Management—National Research Institute. The period with the average daily air temperature ≥ 5 °C was considered to be the growing season. To determine the dates of the beginning and end of the growing season, the Gumiński method was applied. The time and extent of changes in parameters of the growing season were significantly dependent on the variability of the macro-scale circulation types (AO, NAO, EA, SCAND, EA/WR) affecting the atmosphere circulation over Poland. The Atlantic Oscillation had the greatest impact on the beginning of the growing season. In turn, the end of the growing season was most strongly regulated by the East Atlantic circulation.

## 1 Introduction

In the Northern Hemisphere, the 1983–2012 period was probably the warmest 30-year period in the last 1400 years (IPCC 2013). The consequence of the increase in air temperature is the extension of the growing season in Europe, which influences the modification of phenological phases of individual plants (Menzel and Fabian 1999; Chmielewski and Rötzer 2001; Chmielewski et al. 2004). Changes in thermal conditions may, however, also have adverse effects on agriculture (Nieróbca 2009). Changes in the start and end dates and the length of the growing season combined with the consequences in plant ecosystems may lead to an increase in the amount of accumulated carbon in the long run, which will cause changes in the climate system (Linderholm 2006). In the coming years, the further increase in the length of the growing season in Poland is forecast. Nieróbca et al. (2013) indicated that in the perspective of 2030, the growing season in central Poland may increase by 10–14 days in comparison to the reference period of 1971–2000, and in the perspective of 2050 by 18–27 days, while in south-western Poland, respectively, by 11–17 days and 22–30 days. A similar trend was forecast for Norway by Skaugen and Tveito (2004) in the perspective of 2050.

Thermal conditions and their variability are influenced by atmospheric circulation. The impact of the NAO on changes in selected climate elements in Europe, including air temperature, was the subject of research by Trigo et al. (2002). Jaguus (2006) analyzed the impact of the NAO and AO on the spatial and temporal variability of thermal periods in the Eastern European Plain. The dependence of the variability of parameters of the growing season in Finland on macro-scale circulation types has been examined by Irannezhad and Kløve (2015). According to Marsz and Żmudzka (1999), the variability of the NAO indicator explains the variability of the beginning and the length of the growing season in Poland. Many studies based on phenological observations indicate an earlier date of the beginning of the growing season in the second half of the twentieth century, which is caused by the warming associated with the North Atlantic Oscillation (D'Odorico et al. 2002; Stenseth et al. 2002; Menzel 2003; Aasa et al. 2004).

The main objective of the article was to determine the impact of macro-scale circulation types on the beginning and end of the growing season in Poland in 1966–2015. The implementation of the main objective was preceded by the

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determination of long-term and spatial variability of the start and end dates and the length of the growing season.

## 2 Data and research methods

The basis for the study was daily values of the average air temperature from 30 stations located in Poland from the period of 1966–2015 (Fig. 1). The data were obtained from the resources of the Institute of Meteorology and Water Management—National Research Institute.

The start and end dates of the growing season were determined based on the above-mentioned data. The period with the average daily air temperature ≥ 5 °C was considered to be the growing season (Carter 1998; Skaugen and Tveito 2004; Linderholm et al. 2008; Szyga-Pluta 2011; Żmudzka 2012; Radzka 2013). The mathematical formulas proposed by Gumiński (1948) were used to determine the start and end dates of the aforementioned period. This method assumes the following: monthly average temperature falls on 15th day of a month, each month has 30 days, and monthly temperature changes are evenly distributed. The formulas used were:

$$x = 30\left[(td - t1)/(t2 - t1)\right],$$

$$x = 30\left[(t1 - td)/(t1 - t2)\right],$$

where $td$ is the threshold temperature of the growing season (5°C); $t1$ is the average temperature in the month preceding the threshold temperature; $t2$ is the average temperature in the month following the threshold temperature; $x$ is the number of days between the day with the threshold temperature and the 15th day of the preceding month.

The number of days calculated on the basis of the aforesaid formulas is added to the 15th day of the month preceding the threshold temperature. If the sought number is greater than 15, when adding, one should consider the actual number of days in a given month. The obtained date is the beginning or end of the separated period. The Gumiński method is widely adopted in determining the growing season and thermal seasons (Skowera and Kopeć 2008; Kępińska-Kasprzak and Mager 2015; Czernecki and Miętus 2017; Tomczyk and Szyga-Pluta 2017, 2018).

Subsequently, changes were determined in the beginning and end of the growing season and in the length in the analyzed multi-year period. To this end, the non-parametric Mann–Kendall test was used to detect the trend in the time series. The strength of the trends of characteristics in the multi-year period was determined by Sen's non-parametric method (Salmi et al. 2002). Sen's method adopts a linear trend model, $f(t) = Qt + B$, where $Q$ is an estimator

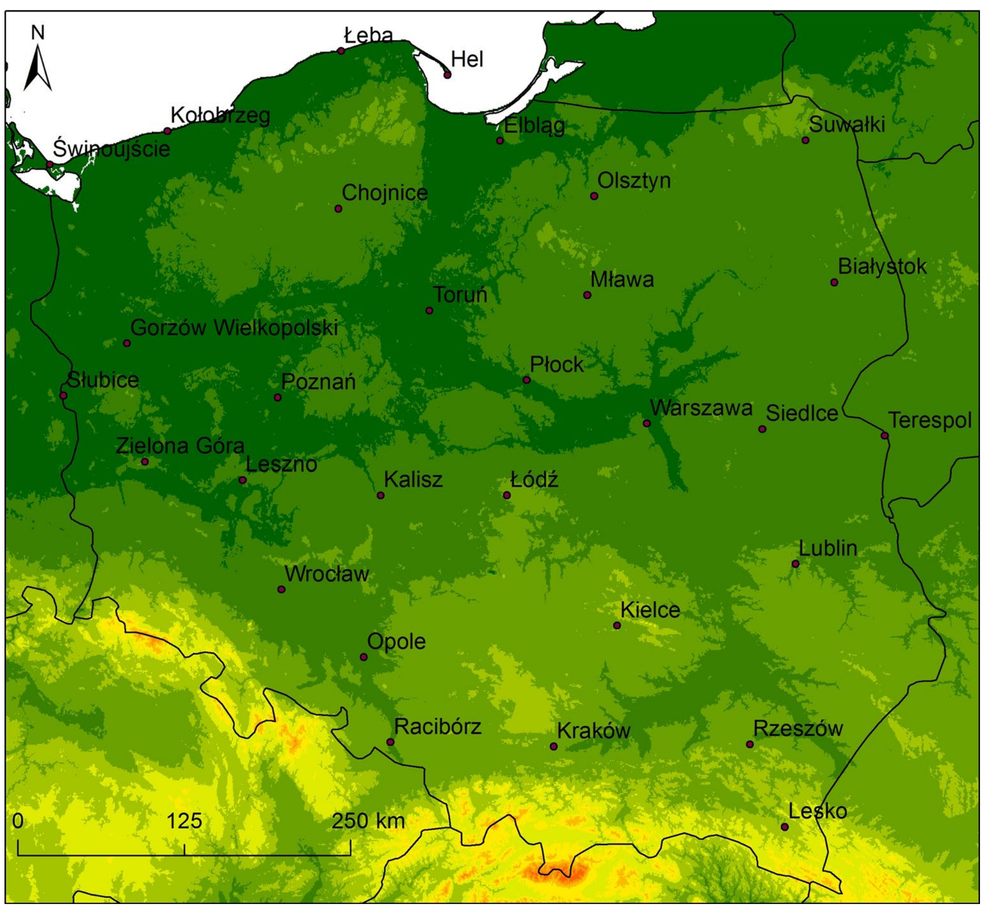



**Fig. 1** Locations of meteorological stations

of the linear regression coefficient (trend strength); *B* is a free term.

In the next step, the effect of macro-scale circulation types on the beginning and end of the growing season was examined. For this purpose, Spearman's rank correlation coefficient ($r_s$) was calculated between the start/end date, expressed as the consecutive number of a day in a year, and the index value of each circulation type. For the start dates of the growing season, the average values of indices from February to April were taken into account, while in the case of end dates, average values from October to December were taken into account. Monthly indices of the following five types of circulation relevant for Central Europe: Arctic Oscillation (AO), North Atlantic Oscillation (NAO), East Atlantic (EA), East Atlantic/Western Russia (EA/WR), Scandinavia (SCAND) were obtained from the databases of Climate Prediction Center (CPC) NOAA (1966–2015). The types of circulation specified in the CPC database were determined by means of the principal components analysis based on the monthly values of 500 hPa isobaric surface anomalies (Barnston and Livezey 1987).

The Arctic Oscillation (AO) is a type of atmospheric circulation in the Northern Hemisphere, dominating in particular during the winter. The positive phase of the AO is associated with lower than normal pressure in the Arctic region and higher at moderate latitudes. As a result, the inflow of Arctic air masses to lower latitudes is blocked. In turn, the negative phase of the AO is associated with higher than average pressure in the Arctic and lower at moderate latitudes. This situation slows down and shifts the jet stream to the south, which promotes the advection of the Arctic air masses to the south (Higgins et al. 2002; Kang et al. 2014). A regional manifestation of the Arctic Oscillation is the North Atlantic Oscillation (NAO), which is a bipolar type of circulation with centers in the region of Iceland and the Azores Islands. The positive NAO phase is associated with negative pressure anomalies in the area of the Icelandic Low and positive anomalies in the Azores High. Consequently, there is a large pressure gradient over the North Atlantic and intensive advection of humid and warm air masses from the west and the south-west over Northern, Western and Central Europe. The reverse distribution of the pressure anomalies means the negative phase of the NAO, which is characterized by the inhibition of the western flow and the inflow of dry and cool air masses from the north-east (Hurrel 1995; Hurrel and Deser 2010). The positive phase of the NAO brings mild winters in Central Europe, and the negative phase means cold and snowy winters (Bednorz 2008; Salmaso and Cerasimo 2012). Like the North Atlantic Oscillation, the system with two centers in the north–south line is the East Atlantic type (EA). This system is shifted towards the south-east of the NAO, and its southern center is associated with the intertropical circulation (Barnston and Livezey 1987). The positive phase of the EA is associated with a deep system of low pressure over the Atlantic, ensuring the advection of warm air masses over Europe. In turn, in the negative phase, there is a high pressure system created over the Atlantic that brings cool and dry air masses (Josey et al. 2011; Mikhailova and Yurovsky 2016). The Scandinavian type (SCAND) is the next macro-scale type of circulation that shapes weather conditions in Europe. It is characterized by a strong high—occurring in the positive phase over the Scandinavian Peninsula with its center over Finland, while the area of lower pressure extends from Western Europe to Eastern Russia and Western Mongolia. The positive SCAND phase is associated with a blocking situation with higher pressure over Scandinavia and Western Russia, while the negative phase is associated with lower pressure than the average over Northern Europe (Bueha and Nakamuta 2007; Liu et al. 2014; Nojaroc 2017). The least-affecting type of circulation in connection to climate and weather in Central Europe is the Eastern European (EA/WR) type characterized by two centers located latitudinally. In the positive phase, the low pressure area is located over Western Russia, while over Western Europe and the British Isles, the high is located. In the positive phase, such a system causes the advection of air masses from the northern sector, while the reverse system in the negative phase promotes advection from the southern sector (Krichak and Alpert 2005; Ionita et al. 2014; Lim 2015). To provide additional information, multiple regression was calculated ($R^2$) between five types of circulation (AO, NAO, EA, SCAND, EA/WR) and the dates of the beginning and end of the growing season in Poland.

## 3 Results

### 3.1 Description of the growing season

The beginning of the growing season proceeded from the south-west to the north and northeast of Poland. It was recorded the earliest in Słubice—on 18 March, and the latest in Suwałki—on 7 April (Table 1). In the analyzed multi-year period, in 93% of stations, the growing season started the earliest in 1990. In the west of the country, it was already on 29 January (Słubice), while in the north-east it was on 18 March (Suwałki). On the other hand, 43% of stations had the latest start in 1997 and it fluctuated from 23 March (Świnoujście) to 21 April (Lesko). In other stations, the latest start occurred mainly in 1970 (north-western Poland) and 1980 (east coast and south-western Poland). However, the latest end of the growing season in the analyzed multi-year period occurred on 5 May 1970 in Kołobrzeg. The above data show that the potential start time of the growing season in the research area was 97 days (from 29 January to 5 May), and in individual stations, it fluctuated from

**Table 1** Characteristics of the growing season in 1966–2015 in Poland

| Station | The beginning of the growing season | | The end of the growing season | | The length of the growing season | |
|---|---|---|---|---|---|---|
| | Average | Changes (days/10 years) | Average | Changes (days/10 years) | Average | Changes (days/10 years) |
| Białystok | 02–04 | **−2.0** | 29–10 | 0.9 | 211 | **3.5** |
| Chojnice | 02–04 | **−3.9** | 02–11 | 1.7 | 215 | **5.4** |
| Elbląg | 29–03 | **−2.5** | 07–11 | 0.9 | 224 | **3.6** |
| Gorzów Wielkopolski | 21–03 | −2.0 | 10–11 | 1.5 | 235 | **3.7** |
| Hel | 05–04 | **−3.6** | 16–11 | **2.6** | 226 | **6.8** |
| Kalisz | 23–03 | −1.1 | 10–11 | **2.2** | 233 | **3.8** |
| Kielce | 29–03 | −1.7 | 01–11 | 1.5 | 218 | **3.6** |
| Kołobrzeg | 29–03 | **−4.1** | 15–11 | 1.1 | 232 | **6.0** |
| Kraków | 23–03 | −1.6 | 06−11 | **1.9** | 229 | **3.1** |
| Lesko | 28–03 | −0.3 | 06–11 | **1.8** | 224 | 2.5 |
| Leszno | 21–03 | −1.6 | 10–11 | **1.8** | 234 | **3.7** |
| Lublin | 28–03 | −1.4 | 02–11 | 1.3 | 220 | **3.1** |
| Łeba | 04–04 | **−4.2** | 16–11 | **2.0** | 227 | **6.9** |
| Łódź | 26–03 | −1.7 | 06–11 | **2.2** | 227 | **4.1** |
| Mława | 31–03 | **−2.8** | 31–10 | **1.3** | 215 | **4.4** |
| Olsztyn | 01–04 | **−3.1** | 01–11 | 1.3 | 215 | **4.6** |
| Opole | 19–03 | −1.1 | 12–11 | **2.4** | 239 | **3.5** |
| Płock | 25–03 | −1.7 | 08–11 | 1.6 | 228 | **3.3** |
| Poznań | 21–03 | −1.8 | 09–11 | 1.6 | 234 | **3.8** |
| Racibórz | 19–03 | −0.5 | 11–11 | **1.8** | 237 | 2.4 |
| Rzeszów | 24–03 | −1.4 | 07–11 | **2.1** | 229 | **3.8** |
| Siedlce | 29–03 | **−2.1** | 03–11 | 1.8 | 220 | **4.0** |
| Słubice | 18–03 | −1.1 | 14–11 | 1.4 | 242 | **3.5** |
| Suwałki | 07–04 | **−2.8** | 25–10 | 0.9 | 202 | **4.2** |
| Świnoujście | 25–03 | **−3.1** | 15–11 | 1.6 | 236 | **5.6** |
| Terespol | 28–03 | **−1.8** | 01–11 | **2.3** | 219 | **4.6** |
| Toruń | 26–03 | **−2.7** | 07–11 | 1.5 | 228 | **4.6** |
| Warszawa | 25–03 | **−2.0** | 06–11 | **2.0** | 227 | **4.0** |
| Wrocław | 19–03 | −1.6 | 11–11 | **2.5** | 238 | **4.0** |
| Zielona Góra | 20–03 | −1.7 | 09–11 | 1.4 | 235 | **3.2** |

Bold: statistically significant changes

38 days in Suwałki to 95 days in Kołobrzeg. In the investigated years, an increasingly early beginning of the growing season was found. The recorded changes were statistically significant in coastal stations and in north-east Poland. The largest changes occurred in Łeba (−4.2 days/10 years) and Kołobrzeg (−4.1 days/10 years) (Table 1). The smallest changes were recorded in southern and western Poland.

The end of the growing season proceeded from the north-east to the west and north of the country. On average, the end of the growing season was recorded the earliest in Suwałki—on October 25, and the latest in Hel and Łeba—on November 16 (Table 1). In the analyzed multi-year period, in most stations, the earliest end of the growing season occurred in 1993, 1973 and 1998. In general, in these years, the ending was recorded in the third decade of October. However, the earliest ending was recorded in Terespol in 1977, already on 8th October. In turn, the latest end of the growing season in most stations occurred in 2015 (central and south-western Poland), 2000 (eastern and south-eastern Poland) and 2006 (north-western Poland). At that time, it was recorded even in the second half of December. However, the latest ending was recorded in the 2006 season, which ended on 19 January 2007. The above-mentioned data show that the potential end time of the growing season within the research area was 104 days (from 8 October to 19 January), and in individual stations it fluctuated from 33 days in Kraków to 86 days in Słubice. In the investigated years, an increasingly late end of the growing season was found. The recorded changes were statistically significant on the east coast, in central and southern Poland. The largest changes occurred in Hel (2.6 days/10 years) and Wrocław (2.5 days/10 years) (Table 1). The smallest changes were recorded in north-eastern Poland.

In Poland, the average length of the growing season was 227 days and it changed from 202 days in Suwałki to 242 days in Słubice (Table 1). Apart from the coastal stations, the standard deviation fluctuated at a similar level, 13–15 days. The increase in the length of the growing season took place from the north-east to the south-west. In 56% of stations, the shortest growing season occurred in 1997, and its length ranged from 180 days (Mława) to 227 days (Świnoujście). However, the shortest growing season in the surveyed multi-year period was recorded in Suwałki in 1992, which lasted only 179 days. It began on 16 April and ended on 11 October. In turn, in 63% of stations, the longest growing season occurred in 1990, and its length then fluctuated from 229 days (Suwałki) to 295 days (Kołobrzeg). In addition, in two stations (Chojnice, Opole) the same length as in 1990 was recorded (respectively) in 2015 and 2014. Nevertheless, the longest growing season in the analyzed years was recorded in Słubice in 2006, which lasted 297 days. It began on 29 March 2006 and ended on 19 January 2007. In the discussed period, an increase in the length of the growing season was recorded, which, apart from two stations in the south of the country, was statistically significant ($p \leq 0.05$). The most intense increase in the length of the growing season was recorded in north-western Poland, in particular at seaside stations, i.e., in Łeba (6.9 days/10 years) and Hel (6.8 days/10 years) (Table 1). Equally high growth was recorded in north-eastern and eastern Poland, for example, in Olsztyn and Terespol (4.6 days/10 years).

### 3.2 Influence of macro-scale circulation types on the beginning and end of the growing season

Despite the high spatial and temporal variability of the start dates of the growing season, the vast majority (> 99%) were recorded in the months from February to April. Therefore, in the analysis of the impact of macro-scale circulation types on the starting date of the growing season, 3-month (February–March–April) average values of indices of each type were taken into account. A simple linear relationship was sought for between the nature of the circulation area and the date of the beginning of the warm growing season, using the Spearman correlation. At the number of cases $N = 50$, correlation coefficient $|r_s| > 0.235$ was statistically significant at the level $p = 0.05$.

Among the types of circulation identified in the Northern Hemisphere, the Arctic Oscillation had the greatest impact on the date of beginning of the growing season in Poland. Spearman's rank correlation coefficient ($r_s$) was negative and statistically significant throughout the country, which means that the negative phase of the AO (negative index) significantly delayed the onset of the growing season; while in the positive phase of the AO—with dominant western circulation—at the turn of spring, warming came earlier. In most of Poland $r_s$ took values $< -0.4$, and in the west even $< -0.5$ (Fig. 2). Differences in the dates of the beginning of the growing season in positive (index AO > 1) and negative (index AO < −1) oscillation extremes were less than 3 weeks in the west of the country, up to 4 weeks in the western part of the coast. The smallest influence of the AO on the air temperature at the end of winter and early spring was recorded on the south-east and north-east end of Poland ($r_s > -0.3$) and there the differences in the dates of the onset of the growing season in the extremes of oscillations were about a week.

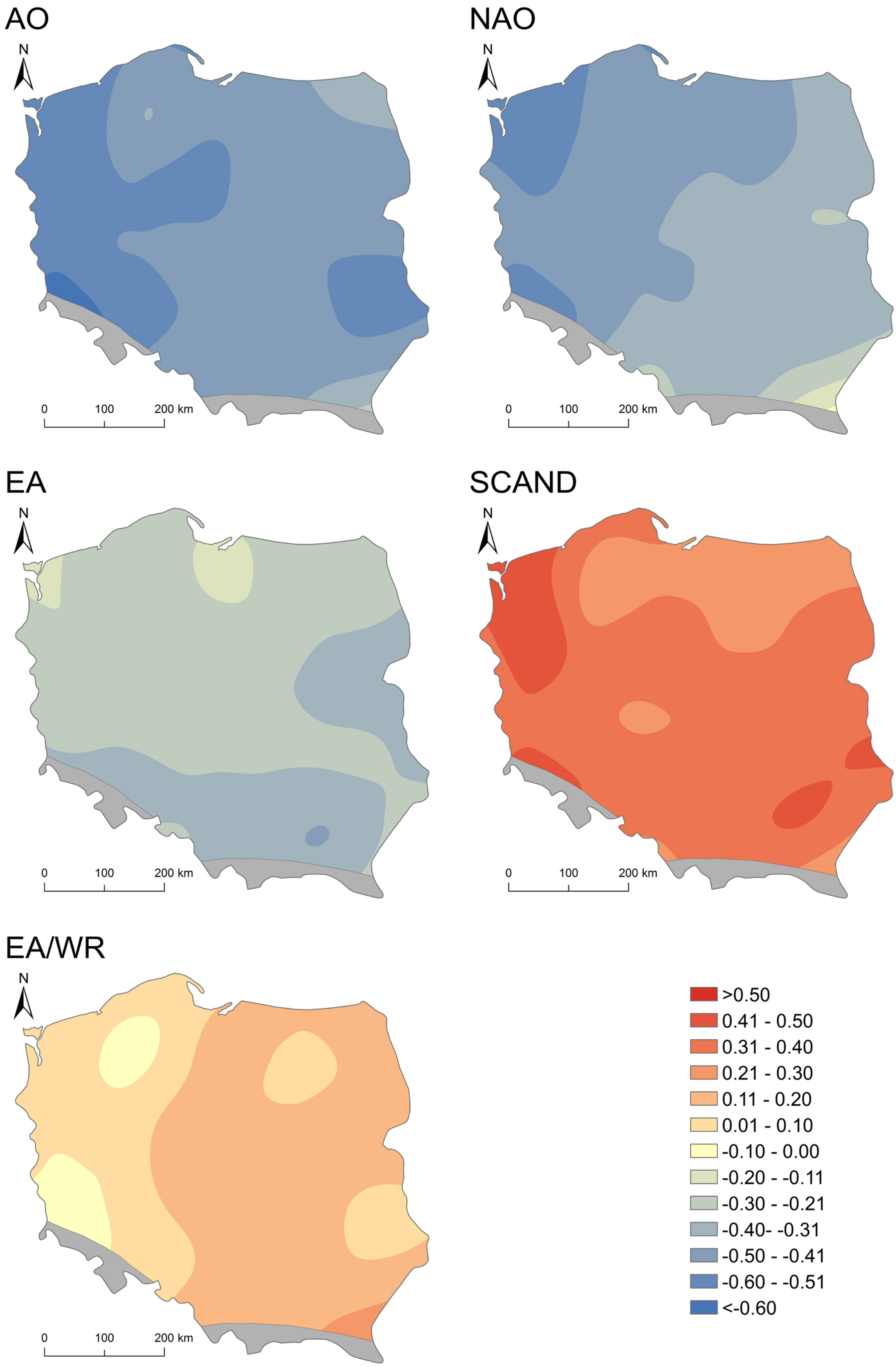
The North Atlantic Oscillation regulated the beginning of the growing season to a lesser extent than the AO, and the dependence—as in the case of the AO—was negative. In the northwest value $r_s$, exceeded −0.5, and in the west and north-west of Poland, where the NAO modified air temperature values most considerably in winter and early spring, $r_s$ was less than −0.4. The impact of NAO decreased in the south-east direction; in the Lesko region $r_s$ was −0.2. In the NAO extremes (index > 1/< −1), the differences in the dates of the beginning of the growing season were the highest in the western part of the coast (about 4 weeks), and the lowest in the east of Poland (1–2 weeks).

The East Atlantic type had a smaller impact on spring air temperature increases in Poland and the correlation coefficient hardly exceed −0.4. Because the EA type pressure centers are shifted southeast of the centers identified in the NAO type, the correlation of EA indices with the dates of the beginning of the growing season was greater in the south of Poland. In the central and northern part of the country $r_s > -0.3$, and in Żuławy $r_s > -0.2$, and it was not statistically significant.

The Scandinavian type was positively correlated with the dates of the beginning of the growing season in Poland, which means that the presence of the high over Scandinavia in the positive SCAND phase caused an inflow of Arctic air masses from the north-east and stopping the temperature rise at the turn of spring. The correlation coefficient was the highest in the northwest and exceeded 0.4, and the lowest (< 0.3) in north-eastern Poland (Fig. 2). In the extremes of this type of circulation (SCAND index > 1/< −1), differences in the dates of the beginning of the growing season exceeded 2 weeks in the west of Poland and at the sea, and in the east of the country, they were about a week.

The last analyzed circulation pattern—the East European type did not have a statistically significant effect on the date of beginning of the growing season in Poland (Fig. 2).

The end dates of the growing season mostly fell (> 99% of cases) upon the months from October to December. The


AO
NAO
EA
SCAND
EA/WR
N
0
100
200 km
>0.50
0.41 - 0.50
0.31 - 0.40
0.21 - 0.30
0.11 - 0.20
0.01 - 0.10
-0.10 - 0.00
-0.20 - -0.11
-0.30 - -0.21
-0.40- -0.31
-0.50 - -0.41
-0.60 - -0.51
<-0.60

◂**Fig. 2** Spearman's correlation coefficient ($r_s$) between average (February–April) indices of macro-scale circulation types and the dates of the beginning of the growing season in Poland in 1966–2015

analysis of the impact of macro-scale circulation types on the end date of the growing season took into account the average indices of circulation types for the months of October–November–December and—like for the start dates—the linear correlation coefficients of end dates with averaged indices of each type of circulation were calculated.

It was proven that the greatest significance for the delay or acceleration of the fall-winter temperature drop had the EA, for which the correlation coefficient exceeded 0.4 in western Poland, except for the coastal belt, where the EA type impact was lower (Fig. 3). Values of the coefficient $r_s$ decreased towards the east and north-east, where they were $< 0.3$. The statistically significant, high positive correlation in the majority of the country meant that the positive phase of the EA and the accompanying south-western inflow of air masses significantly delayed autumn–winter cooling. The positive EA extremes (index > 1) can extend the growing season in central and western Poland by a month compared to the negative extremes of this type of circulation (index < − 1).

The significance of two related types of circulation, the AO and the NAO, was the highest in northern edges of Poland, where the values of coefficient $r_s$ reached statistically significant values ($r_s > 0.3$). In the south-eastern part of the country, the correlation of the dates of the end of the growing season with the AO and NAO indices was negative. This means that in late autumn, the western flow slowing down in favor of the advection from the eastern or south-eastern sector had a positive effect on the air temperature values in south-eastern Poland.

This was confirmed by the positive correlation of the end dates of the growing season with the SCAND index, the strongest and statistically significant in the southern part of the country ($r_s > 0.3$). The high over Scandinavia and North-Eastern Europe in a positive SCAND phase generated an inflow of air masses from the east, which in southern Poland resulted in extending the warm season.

In the negative extremes of the AO and NAO, i.e., with index values < − 1, the growing season ended in the northern part of Poland 2–3 weeks later than in the positive extremes (indexes > 1). Meanwhile, in the south-east, in negative extremes, the growing season was extended by more than a week in comparison with the positive AO and NAO extremes. Positive SCAND extremes lengthened the warm season throughout the country, to over 2 weeks in the west and south-west.

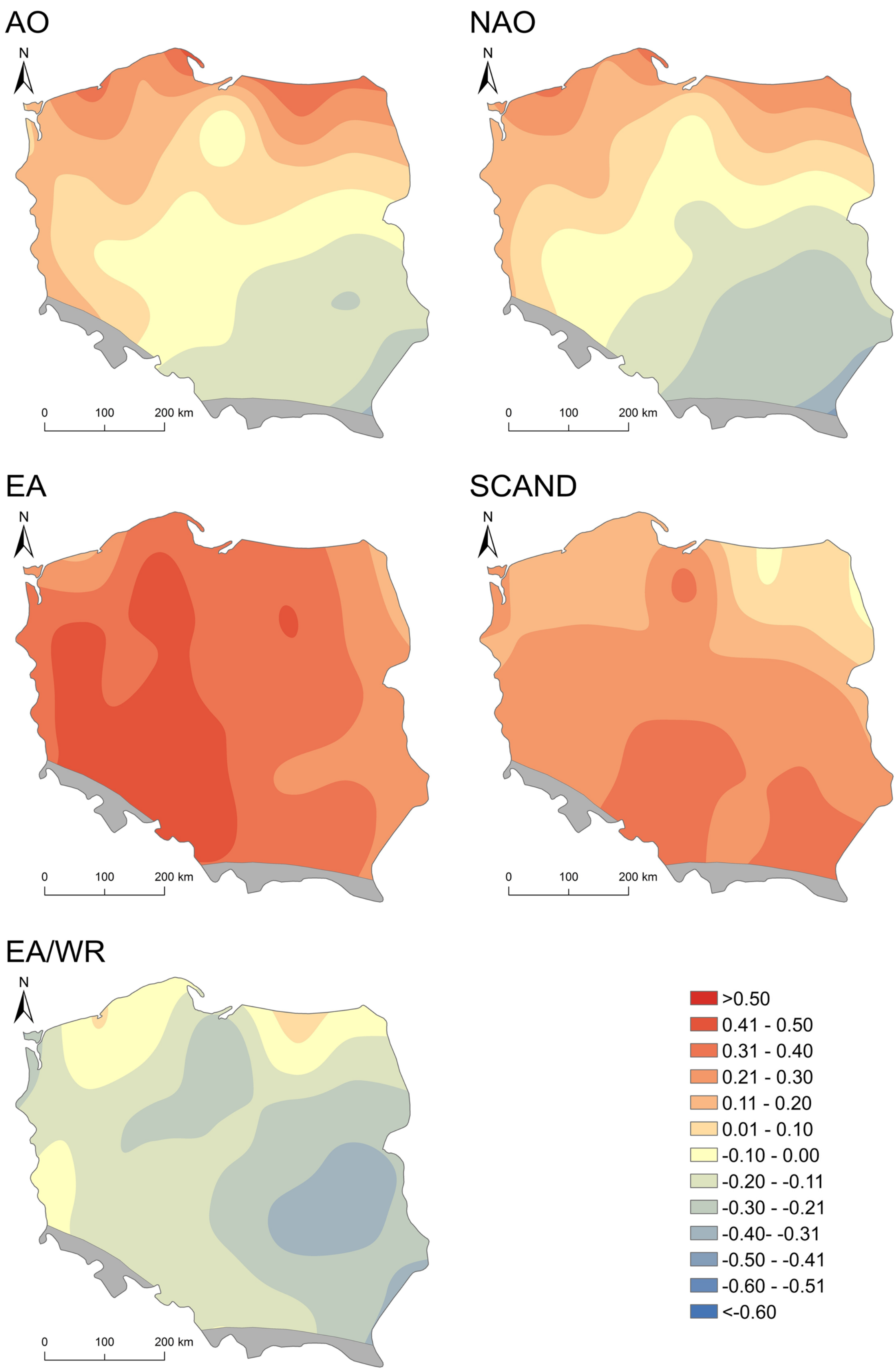
Also the EA/WR type in the autumn and winter season influenced the shaping of the air temperature in Poland. A statistically significant negative correlation in the south-eastern part of the country meant that the formation of a bipolar pressure system with the low over the British Isles and the high over Western Russia, typical of the negative EA/WR phase, caused the advection of air masses from the south and the extension of the growing season in the south-eastern Poland (Fig. 3).

Multiple regression $R^2$, expressing the impact of all five types of circulation included in the study on the dates of the beginning and end of the growing season in the analyzed stations, made it possible to distinguish the regions in which the effect of circulation on the air temperature in the transitional seasons was the most visible (Fig. 4). A stronger influence of circulation on the dynamics of temperature changes was noted at the turn of spring compared to the autumn. The least spatial effect of circulation on temperature in the transitional seasons was manifested in the north-east of Poland ($R^2 < 0.25$), and the most in the west and south-west ($R^2 > 0.45$).

## 4 Summary and discussion

The growing season in the period 1966–2015 in Poland started on average on 26 March and ended on 7 November, the earliest in the south-west, and the latest in the north and north-east of the country. In the analyzed period, the growing season started increasingly early. The most considerable changes occurred in Łeba (− 4.2 days/10 years) and Kołobrzeg (− 4.1 days/10 years). The year–year variability of the dates of the beginning of the growing season is related, according to Bartoszek and Węgrzyn (2011), with the nature of the zonal circulation (the predominant direction of inflow of air masses from the western or eastern sector) in February and March, and the meridional in April. The temperature fluctuations depending on changes in the circulation regime also affect changes in the dates of phenological phases (Chmielewski and Rötzer 2001; Aasa et al. 2004).

The end of the growing season took place from the north-east to the south-west and the coast. The above-mentioned data show that the potential end time of the growing season within the research area was 104 days (from 8 October to 19 January), and in individual stations, it fluctuated from 33 days in Kraków to 86 days in Słubice. The end of the growing season was increasingly late. The recorded changes were statistically significant in the majority of the country except for the north-eastern regions, the Świętokrzyskie Mountains and the Lublin Upland. The largest changes occurred in Hel (2.6 days/10 years) and Wrocław (2.5 days/10 years). The increasingly late ending of the meteorological growing season as the reason for extending its duration in the years 2001–2009 in relation to the years 1971–2000 was reported by Nieróbca et al. (2013). Krużel et al. (2015) stated that the average 4-day increase in the


AO
NAO
EA
SCAND
EA/WR
N
0
100
200 km
>0.50
0.41 - 0.50
0.31 - 0.40
0.21 - 0.30
0.11 - 0.20
0.01 - 0.10
-0.10 - 0.00
-0.20 - -0.11
-0.30 - -0.21
-0.40- -0.31
-0.50 - -0.41
-0.60 - -0.51
<-0.60

◂**Fig. 3** Spearman's correlation coefficient ($r_s$) between the average (October–December) indices of macro-scale circulation types and the end dates of the growing season in Poland in 1966–2015

duration of this period in Poland is the result of both its starting 2 days earlier and ending 2 days later.

In Poland, the average length of the growing season was 227 days and it changed from 202 days in Suwałki to 242 days in Słubice. In the discussed period, an increase in the length of the growing season was recorded, which, apart from two stations in the south of the country, was statistically significant ($p \leq 0.05$). Linderholm et al. (2008) found its lengthening in the Baltic region by approx. 7 days in the second half of the twentieth century. As a result of this study, it was shown that the most intensive increase in the length of the growing season was recorded in north-western Poland, in particular in seaside stations, i.e., in Łeba (6.9 days/10 years) and Hel (6.8 days/10 years). The increase in the length of the growing season in different regions of Poland was also confirmed by other authors, among others, Skowera and Kopeć (2008), Żmudzka and Dobrowolska (2001), Olechnowicz-Bobrowska and Wojkowski (2006), Krużel et al. (2015), Graczyk and Kundzewicz (2016). A similar trend was observed on the basis of different periods and methods also in other regions, including Scandinavia (Carter 1998), Germany (Menzel et al. 2003) and Finland (Irannezhad and Kløve 2015) and also in the western United States (Feng and Hu 2004) and China (Dong et al. 2013). The increase in the length of the growing season in Europe by 10.8 days from the 1960s was found by Menzel and Fabian (1999) on the basis of 30-year observations. This has also been confirmed by later phenological observations (Menzel 2000; Stenseth et al. 2002) The upward trend in the duration of the growing season in north-eastern Europe is on average 1.5 days per 10 years (Linderholm et al. 2008). According to Song et al. (2010) these changes are occurring faster and faster.

The increase in the length of the growing season in Poland in 1966–2015 was mainly due to its earlier beginning, which was confirmed by the results obtained by Olszewski and Żmudzka (1997). Also according to Bochenek et al. (2013), in 2001–2011 in south-eastern Poland, the tendency of lengthening of the growing season was observed, mainly as a result of earlier beginning. In Finland, the cause of vegetation lengthening was spatially diverse: in the north, it was the end of the season, and the earlier beginning in central Finland. On the other hand, on the south-west coast of Finland, both the start and the end of the growing season have been equally shifted (Irannezhad and Kløve 2015). Song et al. (2010) showed that the growing season was prolonged mainly due to an earlier beginning by 1.7 days/10 years in northern China, and in the southern part, the reason was an even postponing of the start and end dates. More significant changes occurring in spring were observed on the basis of phenological phases in Northern and Central Europe (Menzel 2000).

The duration of the growing season is largely influenced by circulation (Marsz and Żmudzka 1999). This has been confirmed by studies showing the impact of the NAO on the variability of phenological phases (D'Odorico et al. 2002; Stenseth et al. 2002; Menzel 2003). Analysis of the impact of macro-scale circulation types on the start and end dates of the growing season in Poland in 1966–2015 showed that the spatially least visible effect of circulation in the transitional seasons was manifested in the north-east of Poland, and it was the most visible in the west and south-west. Among the types of circulation identified in the Northern Hemisphere, the Arctic Oscillation had the greatest impact on the date of beginning of the growing season in Poland. The negative AO phase significantly delayed the onset of the growing season, the most considerably in western Poland. The NAO and EA indices were also negatively correlated with the beginning of the growing period. The Scandinavian circulation showed the opposite effect. The delay in the beginning of the growing season was caused by the occurrence of the positive SCAND phase. The greatest impact was noted in the western part of Poland. There was no significant influence of the Eastern European type on the date of the beginning of the growing season. In Finland, however, this type of circulation had the strongest impact on the parameters of the growing season, especially in the southern part (Irannezhad and Kløve 2015). Marsz and Żmudzka (1999) confirmed the impact of the North Atlantic Oscillation on the beginning of the growing season in Poland. Research by D'Odorico et al. (2002) based on phenological data also showed a significant effect of the NAO in the spring. As demonstrated by Trigo et al. (2002), the NAO influenced the change of the minimum temperature more strongly than maximum temperature, which may explain a stronger temperature rise at the turn of spring.

The most important influence on the date of the end of the growing season had the East Atlantic circulation. The positive phase of the EA caused delayed autumn/winter cooling, especially in western Poland. A positive correlation with the date of the end of the growing season and the AO and NAO indices was demonstrated in the northern and north-western areas of Poland. South-eastern Poland was characterized by a negative correlation with these types of circulation. This is confirmed by the positive correlation of the end dates of the growing season with the SCAND index, the strongest and statistically significant in the southern part of the country. The negative phase of the East European circulation influenced the extension of the growing season, the largest in the south-eastern part of the country. Statistically significant relations between the end of the growing season and the NAO index values in Marsz and Żmudzka (1999) studies were not found.

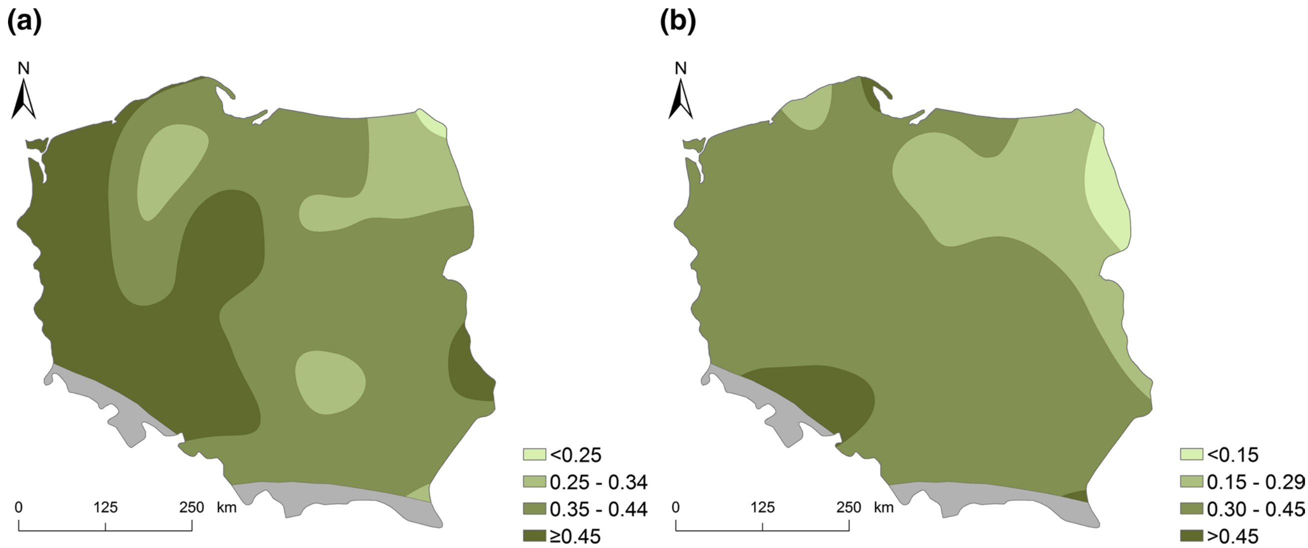



**Fig. 4** Multiple regression ($R^2$) between five types of circulation (AO, NAO, EA, SCAND, EA/WR) and the start (left) and end (right) dates of the growing season in Poland in 1966–2015

The spatially variable impact of macro-scale circulation types on the change in parameters of the growing season observed in Poland was confirmed by the Irannezhad and Kløve (2015) surveys in Finland. They have shown that the EA/WR type had the greatest impact in southern Finland, the EA type in the northern and central part, and the NAO and AO on the south-west coast.

## 5 Conclusion

In the years 1966–2015 in Poland, the growing season was prolonged mainly due to its earlier beginning. The time and extent of changes in parameters of the growing season were significantly dependent on the variability of the macro-scale circulation types (AO, NAO, EA, SCAND, EA/WR) affecting the atmosphere circulation over Poland. The Atlantic Oscillation had the greatest impact on the beginning of the growing season. The end of the growing season is most strongly regulated by the East Atlantic circulation. A stronger influence of circulation on the dynamics of temperature changes was noted at the turn of winter and spring compared to the autumn. The effect of circulation on the temperature in the transitional seasons was the least spatially visible in the north-east of Poland, and the most visible in the west and south-west.



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