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Variability of the Course of Tomato Growth and Development in Poland as an Effect of Climate Change

Robert Kalbarczyk[1], Beata Raszka[2] and Eliza Kalbarczyk[1]
[1]Department of Meteorology and Climatology
West Pomeranian University of Technology in Szczecin
[2]Department of Spatial Economy,
Wrocław University of Environmental and Life Sciences
Poland

1. Introduction

The course of phenological phases play an important role in the shaping of yield quantity and quality (Mozny et al., 2009; Peiris et al., 1996; Tao et al., 2006). The length of the development stages is important for the proper formation of both vegetative and reproductive organs. The main meteorological factor affecting the rate of plant development is air temperature (Ahmed et al., 2004; Chmielewski et al., 2005; Popov et al., 2003; Schleip et al., 2009b; Sysoeva et al., 1997).

Since the mid-20th century significant changes in temperature values have been observed in the growing season of crop plants. For instance, in the years 1961-2000, the average increase in air temperature in Germany, in the February-April period, amounted to 0.41°C/10 years (Chmielewski et al., 2004). In Poland, an increase in average air temperature during each April-October period in 1973-2002, on average, amounted to 0.54°C/10 years (Kalbarczyk E. & Kalbarczyk R., 2010). Similarly, positive temperature trends have been confirmed for the growing seasons of, e.g., onions and cucumber (Kalbarczyk, 2009a, 2009b, 2010a). Positive trends of air temperature in the growing seasons of crop plants have also been confirmed in other parts of the world (Bonofiglio et al., 2009; Matsumoto, 2010; Parey, 2008; Peng et al., 2004).

Since the mid-20th century changes in air temperature values have had influence on the course of the growth and development of plants. All over the world research studies focused on the reactions of fruit trees (Chmielewski et al., 2004; Fujisawa & Kobayashi, 2010), wild-growing plants (Gordo & Sanz, 2009; Kalvāne et al., 2009; Moiseev et al., 2010; Yoshie, 2010), and crop plants (Ahas et al., 2002; Dalezios et al., 2002; Kalbarczyk, 2009a; Mazurczyk et al., 2003; Menzel, 2000) have been conducted. Changes in temperature values lead to changes in duration of particular stages and the whole growing season of plants (Peiris et al., 1996; Song et al., 2008; Tao et al., 2006). Shifts in the course of the phenological phases may be radically different. The phenological phases are influenced by climate change, and depend on the species and a region of the world. Differences include acceleration to time delay of the date of a phenophase (Chmielewski et al., 2004; Jorquera-

Fontena & Orrego-Verdugo, 2010; Lobell et al., 2007; Wang et al., 2008; Xiao et al., 2008). In the summer, a 1°C increase in the minimum temperature resulted in acceleration of the date of maize flowering by 4.2 days (Tao et al., 2006). In Poland, an increase in the average April temperature by 1°C caused acceleration of the emergence date by 2.5 days (medium-early potato) or 1.7 days (medium-late potato) (Kalbarczyk E. & Kalbarczyk R., 2010). An increase in the average May temperature by 1°C caused acceleration of flowering by about 2.5 days for both cultivars of potato. According to Chmielewski et al. (2004) in Germany a 1°C increase in air temperature in the period from February to April caused the beginning of the growing season and flowering of fruit trees to accelerate by about 5 days and the beginning of winter rye shooting to accelerate by 3.8 days. On the other hand, in north-west China, an increase in the minimum temperature by 1°C caused the analysed development stage of cotton to lengthen by 12 days (budding - anthesis) and 9 days (anthesis - boll - opening) (Wang et al., 2008).

Acceleration in the course of plant development caused by a temperature increase, most often leads to reduction in yield quantity. The negative influence of rising temperature, in the period of plant growth and development was discovered, e.g. in the case of winter wheat and rice (Peng et al., 2004; Tao et al., 2006; Wang et al., 2008). Rising temperature, however had a positive effect on the quantity of maize yield in north-east China (Tao et al., 2006). According to the research conducted with the use of simulation models, the influence of rising temperature on crop plant yields may be diverse, as the kind of plant and region of cultivation must be taken into account. Both reduction in yield quantity, as in the case of winter and spring wheat and beans, (Peiris et al., 1996; Wang & Connor, 1996), and its increase, as in the case of potato in the EU, are possible (Peiris et al., 1996; Wolf & Oijen, 2002). Differences in the harvested yield caused by temperature change may be minor or may be a several dozen % yield difference.

The relationship between temperature change and changes in the phenology of crop plants have been researched. The studies on the field cultivation of vegetable plants, however, are relatively rare. Considering the size of production, calculated by means of the yield volume, tomato ranks second to potato, globally. In 2007, over 126.5 m tonnes of tomato were harvested in the world (FAO, 2008). The leading producers among the European Union countries are: Italy (6.0 m tonnes), Spain (3.7 m tonnes) and Greece (1.5 m tonnes). Poland ranks eighth in the EU, with a tomato production of 0.25 m tonnes. Crop plant cultivation plays an important role in Polish vegetal production. In the domestic structure of cultivated vegetables the share of tomato is relatively small, namely about 6% (GUS, 2010). The high thermal requirements of this plant are the reason for its low ranking. The optimum growth temperature is within a range of 22-27°C during the day and 16-18°C at night, and is determined by tomato development stage and light intensity. Temperatures above 30°C and below 10-12°C constitute the so-called developmental maximum and minimum. Reduction in yield is already observed when the temperature exceeds 25°C (Tshiala & Olwoch, 2010). Tomato is sensitive to the cold (0-5°C) and frost. When temperatures drop below 0°C, the plants freeze and die. At least a 4 month frost-free duration period is needed (Babik, 2004). Thus, in Poland, the climate thermal requirements are limited. A wide strip of central Poland, the Wrocław region, and the Sandomierz-Lublin region, situated in the south, are considered the most favourable areas for ground cultivation (Skąpski & Borowy, 2000). The best yield is harvested in the years which are considered by Polish terms, as warm and dry. In Poland, tomato yield slightly exceeds 20 $t \cdot ha^{-1}$ (GUS, 2008).

The domestic cultivated surface of the plant since 2001 has remained almost at the same level. Predicted adaptation of Polish agriculture to climate changes till 2030, depending on the direction of the changes, show the possibility of a considerable lengthening of the farming season. The farming season is defined as the period when doing field work is possible (Kundzewicz & Kowalczak, 2008). A 2-3 month lengthening of the climatic growing season of plants, and more of a possibility for thermophilous plant cultivation are also forecast. Therefore, more years with favourable weather conditions for good yield of field-cultivated tomato is possible.
The first goal of the undertaken study was to determine changes occurring in the course of tomato growth and development. The second goal was to determine tomatoes' dependence on air temperature during its growing season.

2. Material and methods

The results of field experiments on tomato (*Lycopersicon esculentum* Mill), carried out in 22 stations of the Research Centre for Cultivar Testing (COBORU) in Poland in the years 1965-2004 were used in this study. Our study was based on data concerning tomato growth and development. Agrotechnical dates used were: planting up (Pu), the beginning of harvesting (Bh) and the end of harvesting (Eh). Phenological dates used were: the beginning of flowering (Bf) and the beginning of fruit-setting (Bfs). In order to standardise the description of tomato development, the development stages (Bf, Bfs) determined according to the instructions of COBORU were additionally characterised by means of the numerical scale BBCH (Meier, 2001). This scale is employed in European Union countries. A method of determining development stages of monocotyledonous and dicotyledonous plants is used. The analysis in the study also included tomato development stages; four short ones: planting up – the beginning of flowering (Pu-Bf), the beginning of flowering – the beginning of fruit-setting (Bf-Bfs), the beginning of fruit-setting – the beginning of harvesting (Bfs-Bh), the beginning of harvesting – the end of harvesting (Bh-Eh); and a long one: planting up – the end of harvesting (Pu-Eh).
The experimental data of COBORU were collected for all the most commonly cultivated varieties of dwarf, flexible-stemmed tomato examined in a given year. After averaging, the data were accepted as a collective standard of the described plant. The use in the research of the collective standard was based on an assumption that intra-species differences do not obfuscate the sought after general regularities of the species. The field experiments took place in the whole area of Poland, except the submountainous regions located in the south-west and south-east of the country. The submountainous regions were excluded from the analysis on the grounds that field cultivation in Poland does not usually occur 500 metres above sea level.
Field experiments in the years 1965-2004 were conducted according to the methodology of COBORU (Domański, 1998). Tomato was cultivated on soils typical for this plant, i.e. soil rich in nutrients, not very heavy and easily warmed up. Depending on present soil richness, mineral fertilization application fluctuated from 150 to 625 kg per 1 hectare of crop. The average mineral fertilization amounted to 405 kg per 1 hectare of the crop, including N and P_2O_5 which were sown at 120 and 95 kg respectively, and K_2O – at 190 kg each. When full autumn organic fertilization with well-decomposed organic manure or compost at a dose from 20 to 30 t ha^{-1} was used for tomato cultivation, the dose of mineral fertilizers was reduced to 200 kg of NPK per 1 hectare.

In the years 1965-2004, average air temperature data in the period from May to October were collected from all meteorological posts operating at the experimental stations of COBORU. If there was no meteorological post at the location of the tomato experiments, the results coming from a meteorological station of the Institute of Meteorology and Water Management (IMGW) were used in the analysis. The selected IMGW station was situated closest to the COBORU station and best reflected the weather conditions of the conducted experiments. In addition, to determine spatial variability of air temperature, the research used data from 52 stations of IMGW, evenly distributed throughout Poland.

Agrotechnical dates, the dates of phenological phases, tomato development stages, and also thermal conditions of air were characterised with the use of the following statistical indexes: multi-annual average, the value of the highest and the lowest average, absolute minimum and maximum values, the range and standard deviation. Multi-annual average and standard deviation in the 40-year research period were calculated on the basis of data from all considered experimental stations of COBORU, or all meteorological stations of IMGW for the dates and duration of tomato development stages and in the case of air temperature. The range was determined between the highest average value (longest, latest) and the lowest average value (shortest, earliest). Temporal and spatial distribution of the change in the course of tomato development and air temperature were also determined on the basis of their linear trend, determined on the basis of linear regression equation. The study calculated deviations from the average, in the subsequent years of the analysed multi-annual period, in relation to the accepted basic period 1965-2004. Identification of the course of tomato development was carried out on the basis of two statistical parameters: the arithmetic mean and standard deviation. The parameters were determined for the basic period 1965-2004. Criteria and classes are presented in Table 1.

Class	Criterion	Date	Duration of development stages
1	$\xi > \Pi + 2.0\delta$	anomalously late	anomalously long
2	$\Pi + 1.5S < \xi \leq \Pi + 2.0S$	very late	very long
3	$\Pi + 1.0S < \xi \leq \Pi + 1.5S$	late	long
4	$\Pi - 1.0S \leq \xi \leq \Pi + 1.0S$	normal	normal
5	$\Pi - 1.5S \leq \xi < \Pi - 1.0S$	early	short
6	$\Pi - 2.0S \leq \xi \leq \Pi - 1.5S$	very early	very short
7	$\xi < \Pi - 2.0S$	anomalously early	anomalously short

Π - average value from the basic period of 1965-2004, S - standard deviation from the basic period of 1965-2004, ξ - average value from a given year.

Table 1. Classification scale of the agrotechnical dates and duration of tomato development stages in the years 1965-2004.

For example, the date of the beginning of tomato harvesting was considered average (normal) when the date in a given year fulfilled the following condition: $\Pi - 1.0S \leq \xi \leq \Pi + 1.0S$, where Π denotes the average date, δ the value of standard deviation, with both parameters calculated for the basic period 1965-2004. ξ denotes the date recorded in a given year. Similar classifications, but concerning thermal and precipitation conditions were made, among others, by: Pokladníková et al. (2008), Węgrzyn (2007) and Żmudzka (2004).

The relationship between agrotechnical dates and the dates of tomato phenophases, and the average air temperature was determined by means of the simple linear regression analysis. Statistical assessment of the equations was done on the basis of the *t*-Student and *F*-Snedocor tests, the Pearson's correlation coefficient, and a coefficient describing the difference between standard deviation of a dependent variable and a standard error of equation estimation (*S-Sy*) (Dobosz, 2001; Sobczyk, 1998). The occurrence of autocorrelation of random components was checked by means of the Durbin-Watson test. To verify regression equations, the study also used relative forecast error, determined according to the formula:

$$RFE = \frac{y - y_p}{y} \cdot 100\% \quad (1)$$

and average relative forecast error, for all the analysed stations of COBORU and the considered years 1965-2004. An average relative forecast error was calculated according to the formula:

$$ARFE = \frac{1}{n}\sum_{i=1}^{n}\left|RFE\right| \quad (2)$$

where:
y – actual date (day),
y_p – date calculated according to the formula (day),
n – number of years accepted in a time series (number of stations x number of years).
Also determined, were how many times relative forecast error in the analysed multi-annual period 1965-2004 amounted to $\left|RFE\right| \leq 2\%$ and $2\% < \left|RFE\right| \leq 4\%$.

3. Results

3. 1 Temporal and spatial variability of tomato growth and development

3.1.1 Agrotechnical dates and phenological phases

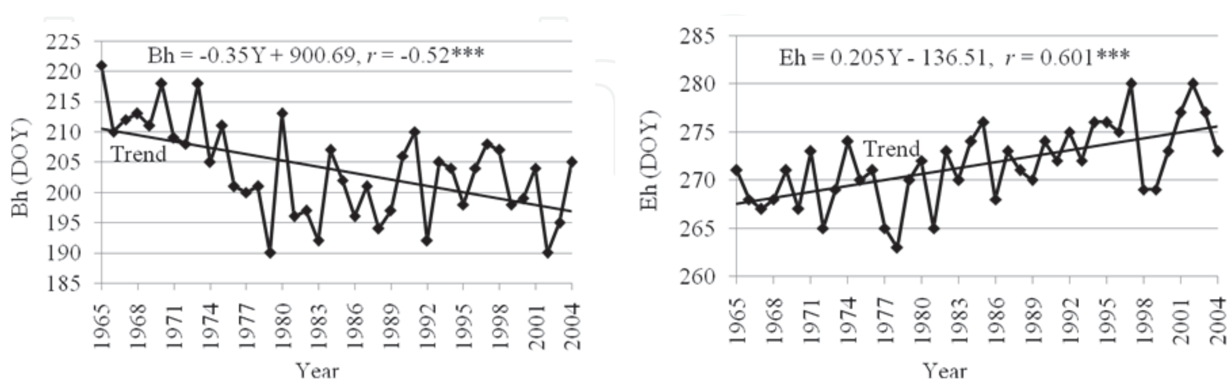
In Poland, in the years 1965-2004, the average date of planting up (Pu) tomato seedlings in the field fell on 21st May (Table 2). The absolute minimum date was 3rd May and the maximum 2nd June. The beginning of flowering (Bf) of the described plant was observed on average on 7th June, and the beginning of fruit-setting (Bfs) on 19th June. The average date for the beginning of harvesting (Bh) fell on 21st July, and the end of harvesting (Eh) on 27th September. The earliest average date was 8th July for the beginning of harvesting and 19th September for the end of harvesting. The latest average date – for the beginning of harvesting was 8th August and 6th October for the end of harvesting. Both absolute minimum and absolute maximum dates of the subsequent agrotechnical dates and the dates of tomato phenophases, were generally different by 2-5 weeks from the average dates. For minimum dates, the bigger differences were in the dates: Pu, Bf and Bfs and in the case of maximum dates: Bh and Eh. The standard deviation of agrotechnical dates and the dates of tomato phenophases fluctuated from about 2 to 8 days. The date of tomato planting up was marked by the lowest standard deviation and the date of the beginning of harvesting by the highest one. The range of the described dates calculated between the average latest and the average earliest date, like standard deviation, was the smallest for planting up and the biggest for the beginning of harvesting. The range swung from a low 7 to as high as 31 days.

Agrophase	BBCH scale	Date (day)						Absolute date (day)	
		mean	latest	earliest	range[2]	S	trend (day/10a)	max	min
Pu[1]	-	21-05	25-05	18-05	7	2.0	-0.6*	2-06	3-05
Bf	61601	7-06	15-06	31-05	15	3.6	-0.7*	23-06	17-05
Bfs	71701	19-06	30-06	10-06	20	4.8	-1.1*	9-07	26-05
Bh[1]	-	21-07	8-08	8-07	31	7.8	-3.5***	26-08	28-06
Eh[1]	-	27-09	6-10	19-09	17	4.0	2.1***	27-10	30-08

Pu – planting up, Bf – beginning of flowering, Bfs – beginning of fruit-setting, Bh – beginning of harvesting, Eh – end of harvesting, S – standard deviation, max – absolute maximum date, min – absolute minimum date, * significant at $p \le 0.1$, *** significant at $p \le 0.01$, [2]between the latest and the earliest date.

Table 2. Statistical characteristics of the agrotechnical[1] dates and the phenological phases of tomato in Poland, in the years 1965-2004.

The analysis of the linear trend of agrotechnical dates and the dates of tomato phenological phases showed a statistically significant, negative temporal tendency. This was a tendency for a year by year acceleration of almost all the considered dates, except for the end of harvesting (Table 2, Fig. 1). The biggest acceleration was found for the beginning of harvesting (-3.5 days /10 years, $p \le 0.01$), and next for the beginning of fruit-setting (-1.1 days /10 years, $p \le 0.1$), definitely the smallest for planting up (-0.6 days /10 years, $p \le 0.1$) and the beginning of flowering (-0.7 days /10 years, $p \le 0.1$). The end of tomato harvesting showed significant delay (2.1 days /10 years, $p \le 0.01$), year by year, in the years 1965-2004. Out of all the analysed tomato dates, the highest correlation coefficient for the linear trend in the years 1965-2004 for all of Poland was determined for the end of harvesting (r = 0.601), and next for the beginning of harvesting (r = -0.52).

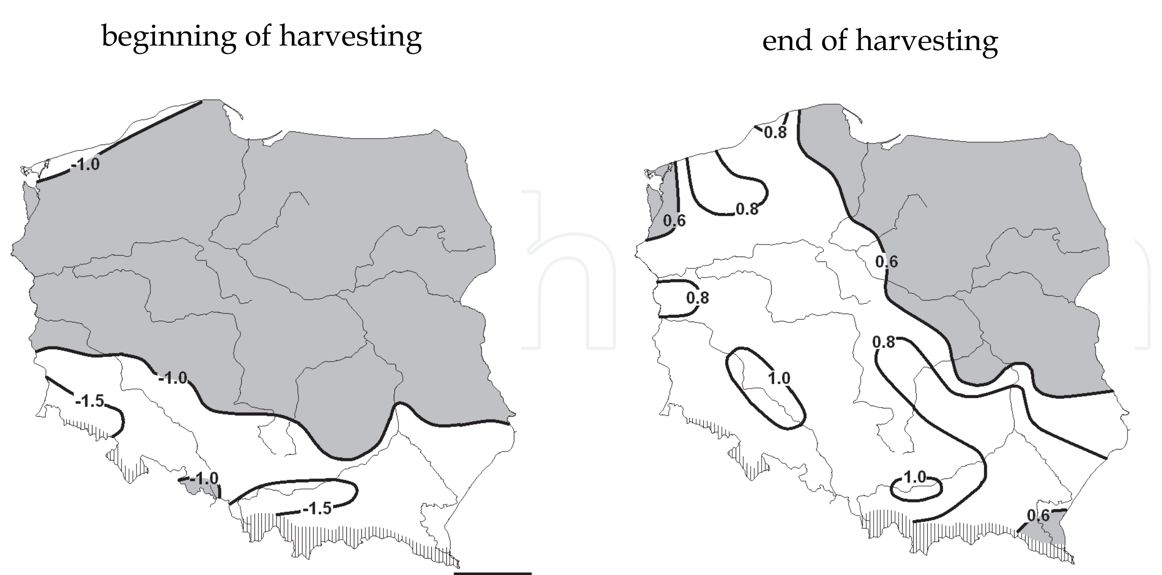


Y – year, r – correlation coefficient, *** significant at $p \le 0.01$.

Fig. 1. Temporal distribution of the dates of the beginning of harvesting (Bh) and the end of harvesting (Eh) of tomato in Poland, in the subsequent years of the analysed multi-annual period 1965-2004.

Acceleration of the date of the beginning of tomato harvesting did not occur evenly throughout the whole country (Fig. 2). Significant acceleration of the beginning of harvesting was proved only in the north-west and in the south (over -1.0 day /10 years). The biggest significant acceleration of the beginning of harvesting was in the south-west and in the Kraków region (over -1.5 days /10 years). Delay of the end of harvesting date, like acceleration of the beginning of harvesting, did not have an even occurrence throughout the whole country. Significant delay of the last date of tomato harvesting was recorded in the western and southern parts of Poland, where it usually oscillated from 0.6 day /10 years to 1.0 day /10 years. The biggest delay of the date (over 1.0 day /10 years) occurred in the Kraków and Wrocław regions.

During the 40-year research period, the date of the beginning of tomato harvesting was decidedly delayed 6 times in comparison with the average domestic date, and accelerated 6 times (Fig. 1, Fig. 3). The results are from agrotechnical dates showing that only once in the first half of the research period, in 1965, the beginning of harvesting was anomalously late. It was very late 2 times; in the years 1970 and 1973. It was late 3 times; in 1967, 1968, 1980. The beginning of harvesting was very early in 1979 and early in 1983. In the second half of the research period, delay of the harvesting date was not recorded, but 4 times the date was accelerated. In 1992 and 2002, the beginning of harvesting date occurred very early. The beginning of harvesting date was early in 1988 and 2003. The end of harvesting date of tomato was marked by the opposite temporal structure. In the first half of the analysed multi-annual period, only the years in which acceleration of the date was recorded, were identified, and in the second half of the analysed multi-annual period only the delay of the date years were identified. The end of tomato fruit harvesting was anomalously early in 1978, very early in 1972, 1977, 1981, and early in 1967 and 1970. Tomato harvesting occurred late in: 1985, 1994, 1995, 2001, 2003, and anomalously late in 1997 and 2002.



the area excluded from analysis, lack of significant influence at the level of $p \leq 0.05$

Fig. 2. Statistically significant, at least at the level of $p \leq 0.05$, linear regression coefficients for the trend of the beginning of harvesting date and the end of harvesting date of tomato in Poland, calculated for 10 years, in the years 1965-2004.

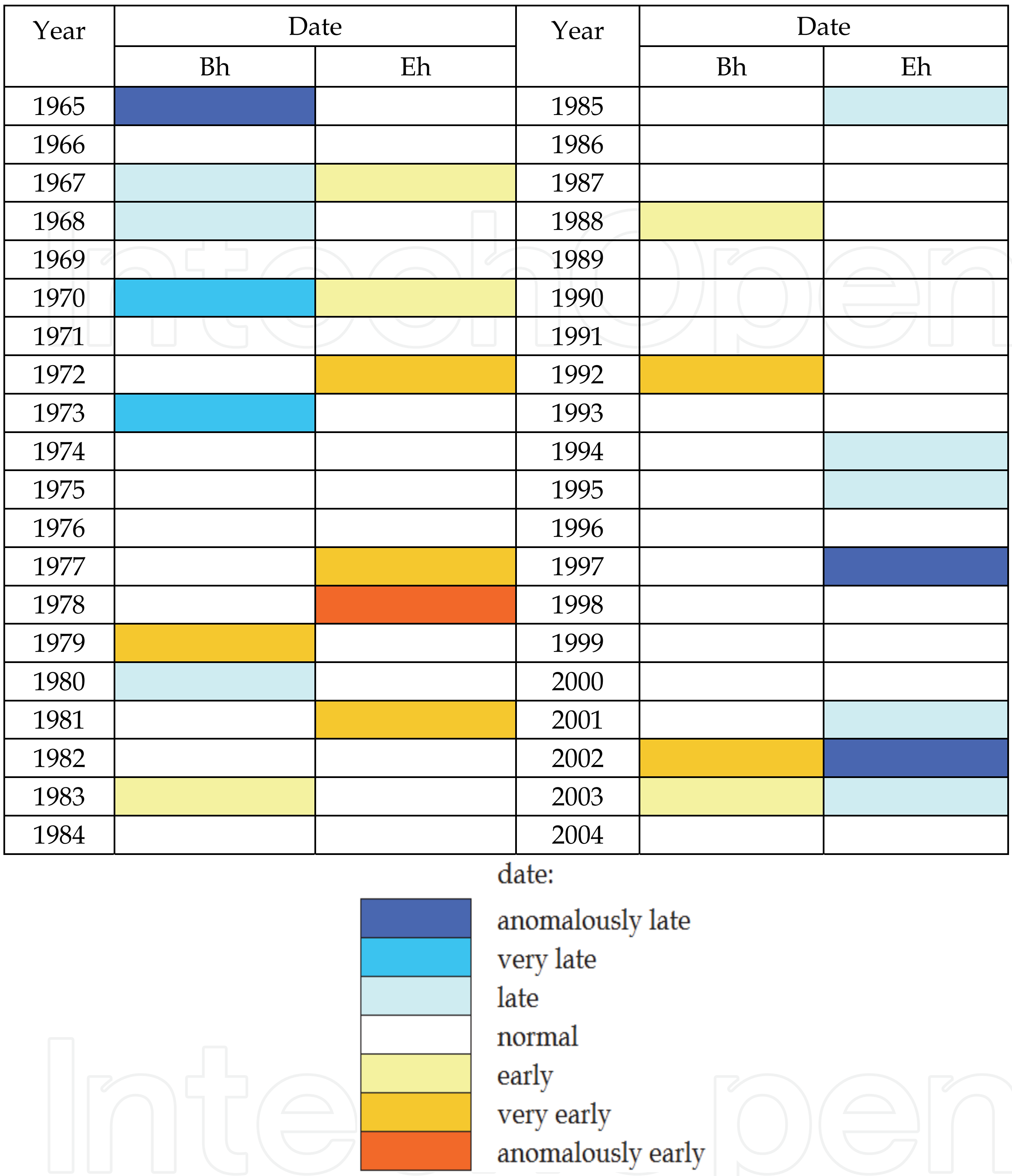


Fig. 3. Identification of the beginning of harvesting date (Bh) and the end of harvesting date (Eh) of tomato in Poland, in the subsequent years of the analysed multi-annual period 1965-2004.

Tomato agrotechnical dates in anomalously extreme years were different from the average domestic date and varied across Poland (Fig. 3, Fig. 4). In 1965, when the date of the beginning of harvesting was identified as anomalously late, deviation from the average multi-annual (1965-2004) date oscillated from less than 4 days to even more than 8 days. The first tomato fruits were harvested in the north and in the south-west of the country at the latest date, 8 days later than the norm. The first tomato fruits were harvested at a slightly earlier date, 4 days later than usual, in the central west, the centre and the south-east. The end of harvesting, especially in 1978, 1997 and 2002 was significantly different from the average domestic date. In 1997 and 2002, deviation from the average multi-annual date for the end of harvesting in Poland, fluctuated mostly from 2 to 6 days in 1997 and from 4 to 8 days in 2002. The biggest delay was recorded in the northern part of the country (> 6 days) in 1997 and in the central-western part (> 8 days) in 2002. In 1978, the last field-cultivated tomato fruits were harvested about 6 to 8 days earlier than the average domestic date. The earliest end of harvesting was recorded in the north-east, north, south-west and locally in the Kielce region.

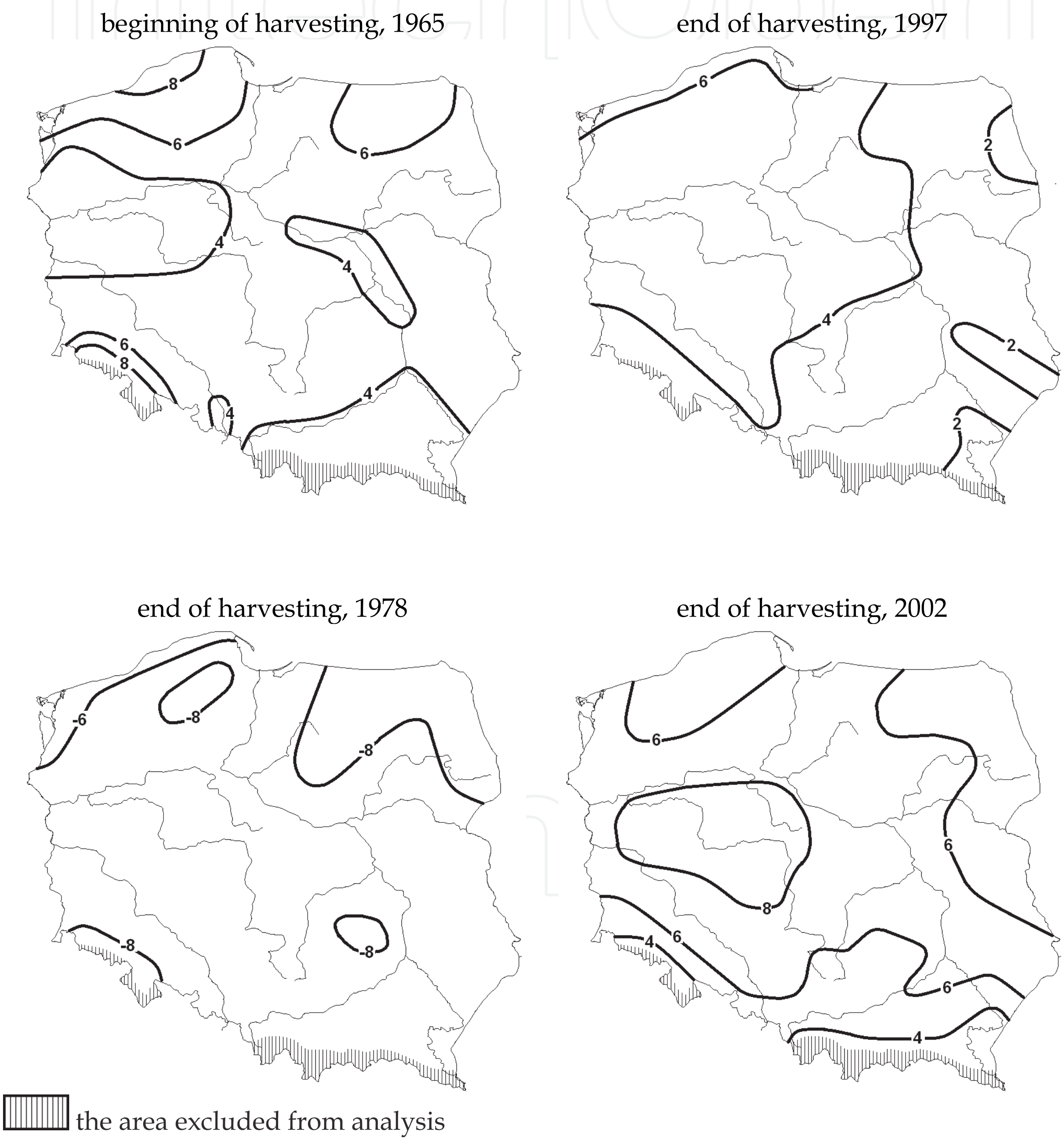


Fig. 4. Deviations from the multi-annual average (1965-2004) in Poland, of tomato agrotechnical dates: the beginning of harvesting in 1965 and the end of harvesting in: 1978, 1997 and 2002.

3.1.2 Development stages

On average, the shortest period of tomato development was the period from the beginning of flowering to the beginning of fruit-setting (Bf-Bfs), lasting only 12 days (Table 3). The longest period of tomato development was the period of tomato fruiting, i.e. from the beginning to the end of harvesting (Bh-Eh), which lasted 68 days. Tomato flowering occurs on average, 17 days after the date of planting up in the field. Tomato flowering occurs earliest after 9 days of planting up in the field and latest after 28 days. The beginning of fruit-setting occurred on average 29 days after the date of planting up. In Poland, the beginning of fruit-setting occurred on average, in the last ten days of May (Table 2). The beginning of tomato harvesting occurred on average, 62 days after the date of planting up. The end of harvesting occurred 130 days after the date of planting up. In the analysed multi-annual period there were also years in which the period from planting up to the end of harvesting (Pu-Eh) lasted 139 days, and at particular stations of COBORU it oscillated from 98 to even 161 days. Absolute minimum duration of development stages oscillated from 4 days in the case of the period Bf-Bfs, to 28 days in the case of the period Bh-Eh.

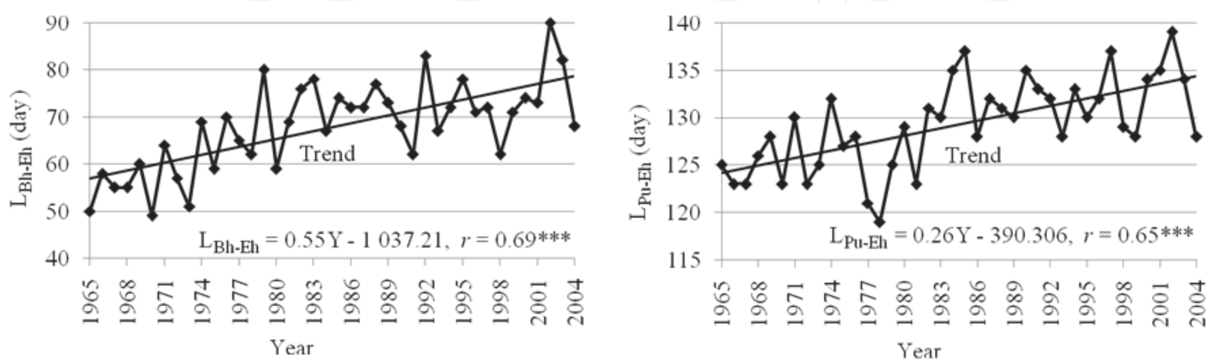
Out of the four considered short periods of tomato development stages, least diverse in terms of duration was the period from the beginning of flowering to the beginning of fruit-setting (Table 3). It was indicated not only by the lowest value of standard deviation (S = 2.0 days), but also by the lowest average value (12 days) and the smallest range (R = 8 days). On the other hand, the periods from planting up to the beginning of flowering (S = 3.6 days) and from the beginning of fruit-setting to the beginning of harvesting (S = 5.2 days) were marked by average diversity of duration. The highest standard deviation (S = 9.5 days) was characteristic of the period from the beginning of harvesting to the end of harvesting. The range between extreme (longest and shortest) average duration periods of tomato development stages, varied from 8 days in the case of the period from the beginning of flowering to the beginning of fruit-setting, to 41 days in the case of the period from the beginning of harvesting to the end of harvesting. In the period from planting up to the end of harvesting, this range amounted to 20 days.

Development stage	Duration (day)						Absolute duration (day)	
	mean	longest	shortest	range[3]	S	trend (day/10a)	max	min
Pu-Bf	17	28	9	19	3.6	n.s.	33	5
Bf-Bfs	12	16	8	8	2.0	n.s.	27	4
Bfs-Bh	33	44	23	21	5.2	-1.4*	80	14
Bh-Eh	68	90	49	41	9.5	5.6***	100	28
Pu-Eh	129	139	119	20	4.7	2.6***	161	98

Pu-Bf – planting up - beginning of flowering, Bf-Bfs – beginning of flowering - beginning of fruit-setting, Bfs-Bh – beginning of fruit-setting - beginning of harvesting, Bh-Eh – beginning of harvesting - end of harvesting, Pu-Eh – planting up - end of harvesting, max – absolute maximum duration, min – absolute minimum duration, n.s. – non-significant at $p \leq 0.1$, [3]between the latest and the shortest duration. The remaining explanations see Table 2.

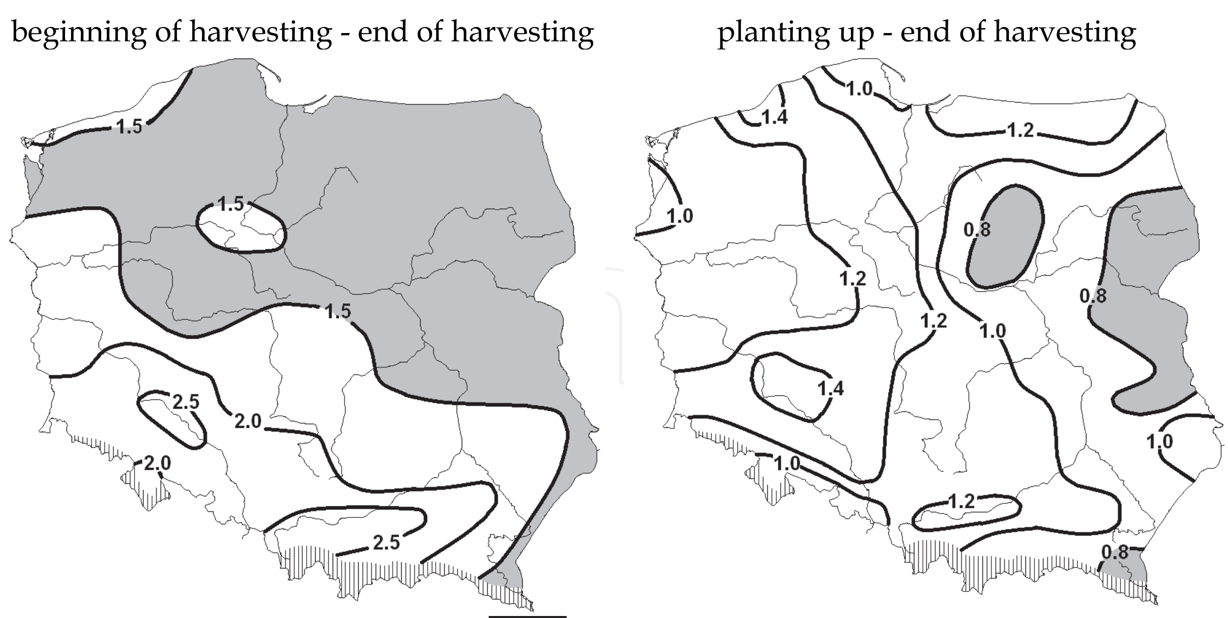
Table 3. Statistical characteristics of duration of tomato development stages in Poland, in the years 1965-2004.

In the years 1965-2004, statistically significant lengthening, at the level of $p \leq 0.01$, of only one out of the analysed four short tomato development stages was seen (Table 3, Fig. 5). In Poland, the period from the beginning of harvesting to the end of harvesting, on average, lengthened by as much as 5.6 days /10 years. In the periods Pu-Bf and Bf-Bfs, no statistically significant examples of shortening or lengthening were found, as opposed to the period Bfs-Bh, which, year by year, became significantly shorter, on average by -1.4 days /10 years. Changes in duration of particular development stages of tomato meant that the whole period lasting from planting up to the end of harvesting, lengthened by as much as 2.6 days /10 years. The correlation coefficient, which was determined for the function best describing the linear trend of development stages, amounted to 0.69 for the period Bh-Eh and 0.65 for the period Pu-Eh.



Y – year, r – correlation coefficient, *** significant at $p \leq 0.01$.

Fig. 5. Temporal distribution of duration from the beginning to the end of harvesting ($L_{Bh\text{-}Eh}$) and from planting up to the end of harvesting ($L_{Pu\text{-}Eh}$) of tomato in Poland, in the subsequent years of the analysed multi-annual period 1965-2004.



the area excluded from analysis, lack of significant influence at the level of $p \leq 0.05$

Fig. 6. Statistically significant, at least at the level of $p \leq 0.05$, linear regression coefficients for the trend of duration from the beginning to the end of harvesting and from planting up to the end of harvesting of tomato in Poland, calculated for 10 years, in the years 1965-2004.

Despite the fact that in the whole country, the period from the beginning of harvesting to the end of harvesting of tomato on average, lengthened by as much as 5.6 days /10 years, in particular regions of Poland, this lengthening predominantly oscillated from 1.5 days /10 years to 2.5 days /10 years (Fig. 6). The biggest lengthening occurred in the south of the country, especially in the Wrocław and Kraków regions (Fig. 2). These were the regions where the biggest acceleration of the beginning of harvesting and at the same time the biggest delay of the end of harvesting were recorded. Changes in duration of the period from planting up to the end of harvesting, in particular regions of the country, were also different than for the whole country (Fig. 6). In Poland, lengthening of the period Pu-Eh usually oscillated from 0.8 day /10 years to 1.4 days /10 years. The biggest changes in duration, over 1.4 days /10 years, of the period Pu-Eh, occurred in south-west Poland in the Wrocław region, and in the north-west in the Koszalin region. No proved significant changes in duration of the Bh-Eh periods took place in the northern, north-eastern and eastern parts of the country. No proved significant changes in duration of the Pu-Eh periods took place in the central-eastern part of the country. Spatial distribution of the duration-change of these two tomato development stages was partially consistent with the distribution of the change of these agrotechnical dates: acceleration of the date of Bh and delay of the date of Eh (Fig. 2).

Changes in duration of the periods Bh-Eh and Pu-Eh were also confirmed by identification of these periods, in the subsequent years of the analysed multi-annual period (Fig. 7). Out of the 40 examined years, there were seven years: 1965-1968, 1970, 1972-1973 with shorter than average Bh-Eh periods recorded. In three of the seven years, the Bh-Eh period was identified as very short, and in four years as short. The Pu-Eh period had a similar distribution of years as the Bh-Eh period, but periods shorter than the average were recorded in: 1966-1967, 1970, 1972, 1977-1978 and 1981. In 1978 the Pu-Eh period was even anomalously short and in 1977 – very short. In the remaining five years, the Pu-Eh period was short. On the other hand, in the years 1983-2004, long periods were recorded. The Bh-Eh period in the following six years: 1979, 1983, 1992, 1995, 2002-2003 and the Pu-Eh period in the following seven years: 1984-1985, 1990, 1997, 2001-2003 were longer than the average. Anomalously long Bh-Eh and Pu-Eh periods were recorded in 2002, and very long ones in 1992 and 1985 and 1997.

In Poland, deviation from the multi-annual average (1965-2004) of the length of the period from the beginning to the end of harvesting in 2002, usually amounted to 8 to 14 days (Fig. 8). The period lasted longest, over 14 days, in the central-western part of the country and in the Warsaw region. The period lasted much shorter – less than 8 days, in northern, south-western and south-eastern Poland. In the case of the long development stage of tomato, i.e. Pu-Eh, deviations from the average in 2002 were lower than in the case of the Bh-Eh period. The long development stage of tomato oscillated generally from 4 to 10 days. The Pu-Eh period lasted the longest; over 10 days, in the central-western part of the country. The Pu-Eh period was slightly shorter, less than 6 days, in the north and north-east. The Pu-Eh period was shortest, less than 4 days, in the south-west and south-east of Poland. In 1978, the Pu-Eh period was also different in its duration from the multi-annual average. The Pu-Eh period was the shortest out of the 40 considered periods in the years 1965-2004. In 1978 the Pu-Eh period was the shortest, less than 8 days, in the north, north-east, south-west and locally in the vicinity of Kielce and Mława.

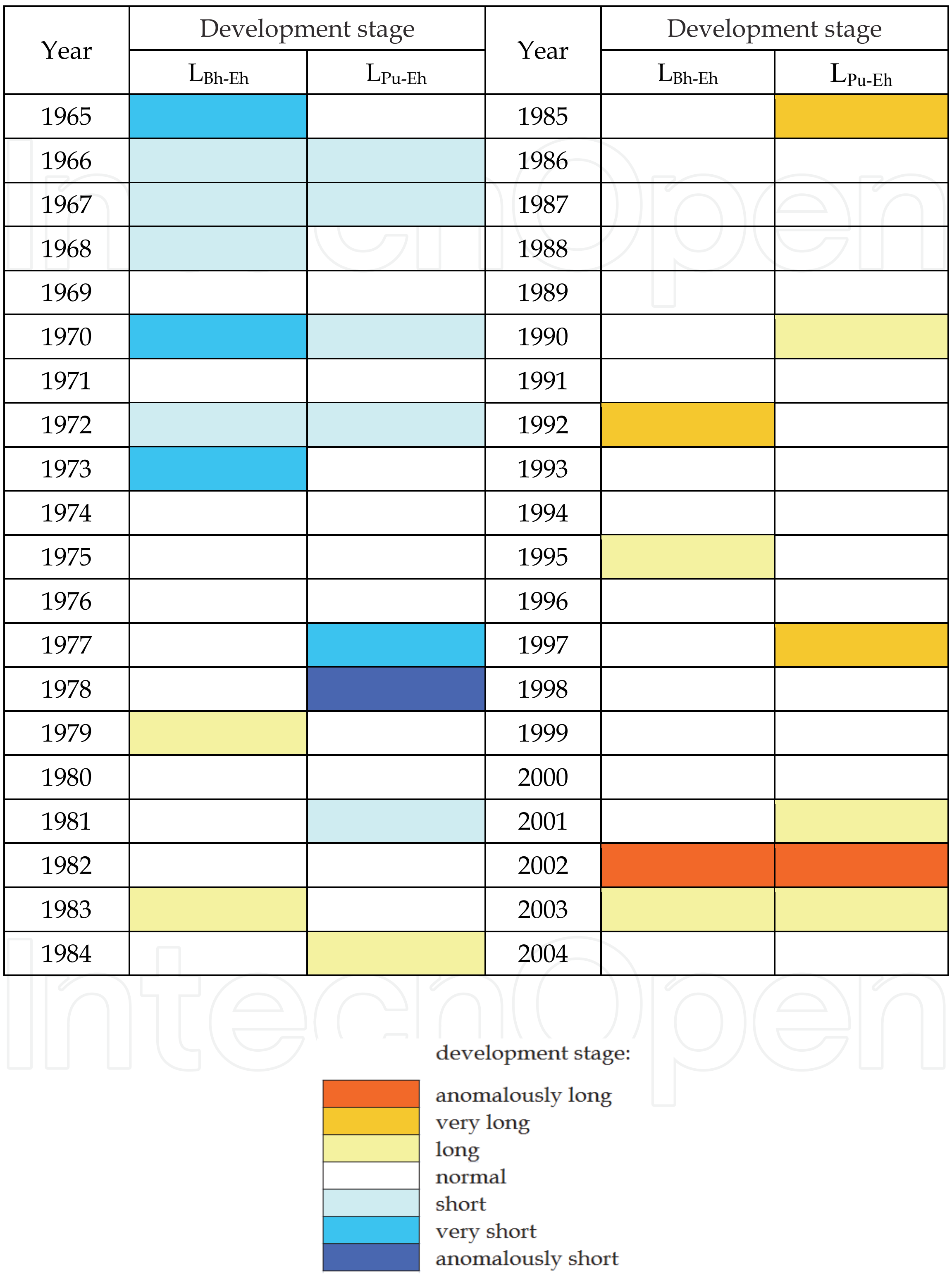


Fig. 7. Identification of duration from the beginning to the end of harvesting (L_{Bh-Eh}) and from planting up to the end of harvesting (L_{Pu-Eh}) of tomato in Poland, in the subsequent years of the analysed multi-annual period 1965-2004.

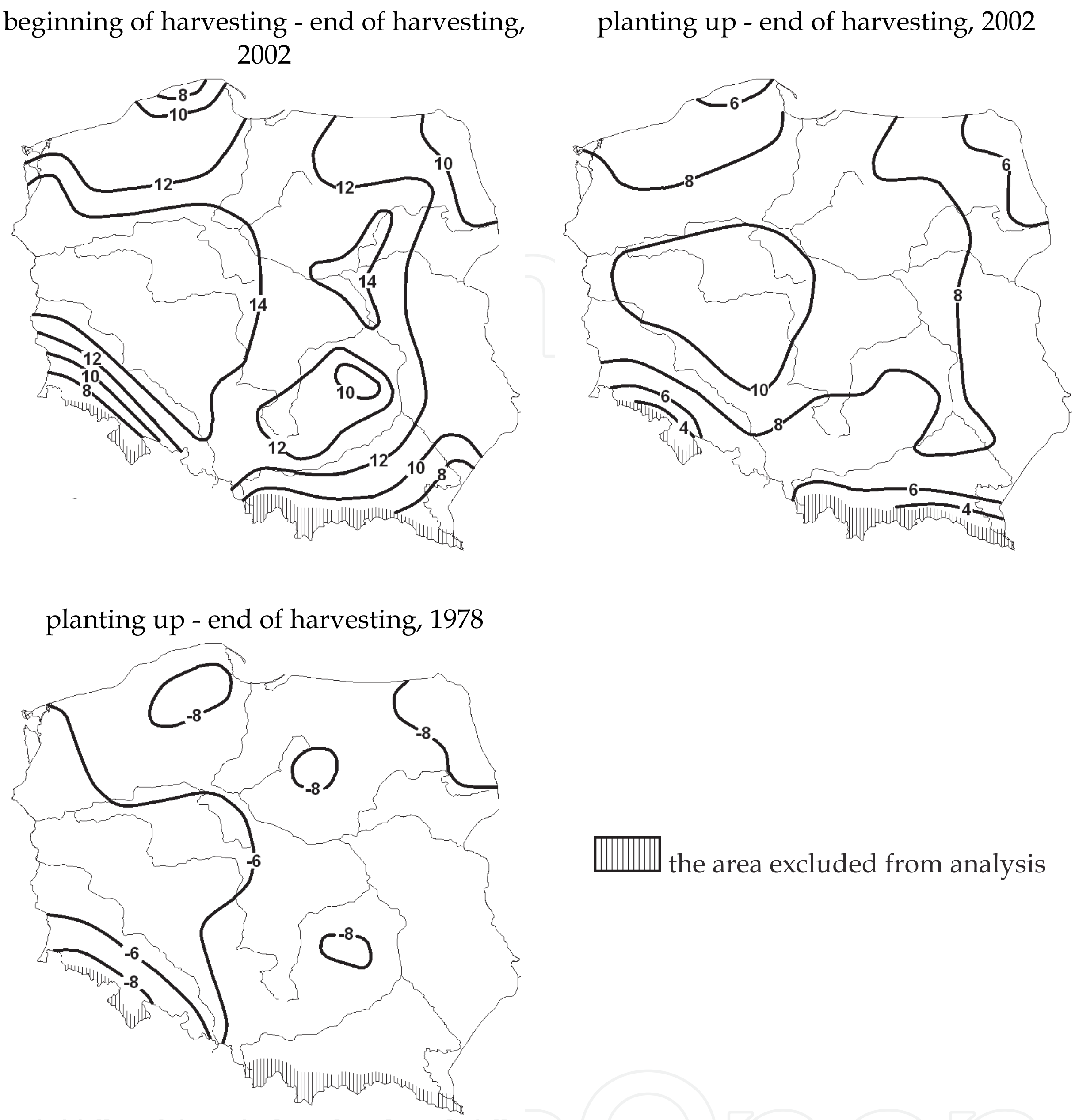


Fig. 8. Deviations from the multi-annual average (1965-2004) in Poland, of duration of tomato development stages: from the beginning to the end of harvesting in 2002 and from planting up to the end of harvesting in: 1978 and 2002.

3.2 Air temperature and its effect on the course of tomato growth and development

Changes in the occurrence of agrotechnical dates and the dates of phenological phases of tomato, which occurred during the 40-year research period (Table 2), are closely related to the course of air temperature (Table 4, Fig. 9). Out of the four dates: Bf, Bfs, Bh and Eh, the strongest relationship with air temperature was proved in the case of the phenological phases: the beginning of flowering (r = -0.77, $p \le 0.01$) and the beginning of fruit-setting (r = -0.82, $p \le 0.01$). A slightly weaker relationship with air temperature, but also significant at the level of $p \le 0.01$, was proved in the case of the agrotechnical dates: the beginning of harvesting (r = -0.56***) and the end of harvesting (r = 0.61***). However, apart from thermal conditions of air, agrotechnical dates of vegetables to a large extent, depend on the course of other agrometeorological conditions. Agrotechnical dates of vegetables also depend on other factors, e.g. organisational work on the horticultural farm (Babik, 2004; Domański, 1998).

The best fitted regression function, in relation to empirical data, was the date of the beginning of fruit-setting (Table 4). This date is confirmed not only by the highest correlation coefficient but also by the values of the *t*-Student and *F*-Snedecor tests and also the coefficient describing the difference between the standard deviation of a dependent variable and equation standard error (*S-Sy*). The date of the beginning of fruit-setting in Poland can be predicted with average relative forecast error amounting only to 1.2%. The occurrence of relative forecast error in the analysed multi-annual period, 1965-2004 within a range of 0-2%, amounted to as much as 82,5%, and within a range of 2-4% - only 17.5%. Out of the four analysed dates of the described plant, three: Bf, Bfs, Bh are negatively affected by thermal conditions of air, i.e. with an increase in temperature there occurred acceleration of the date. If air temperature in May increases by 1^oC, then the date of the beginning of flowering will be accelerated by 1.8 days. When air temperature increases by 1^oC in the period from 10^{th} May to 10^{th} June, then the date of the beginning of fruit-setting will accelerate by 2.2 days. If air temperature increases in the period from 20^{th} May to 20^{th} June, then the date of the beginning of harvesting may even accelerate by 3.1 days. Only the date of the end of harvesting was positively correlated with air temperature in the period from 10^{th} August to 10^{th} September, a drop by 1^oC may delay it by 2.1 days.

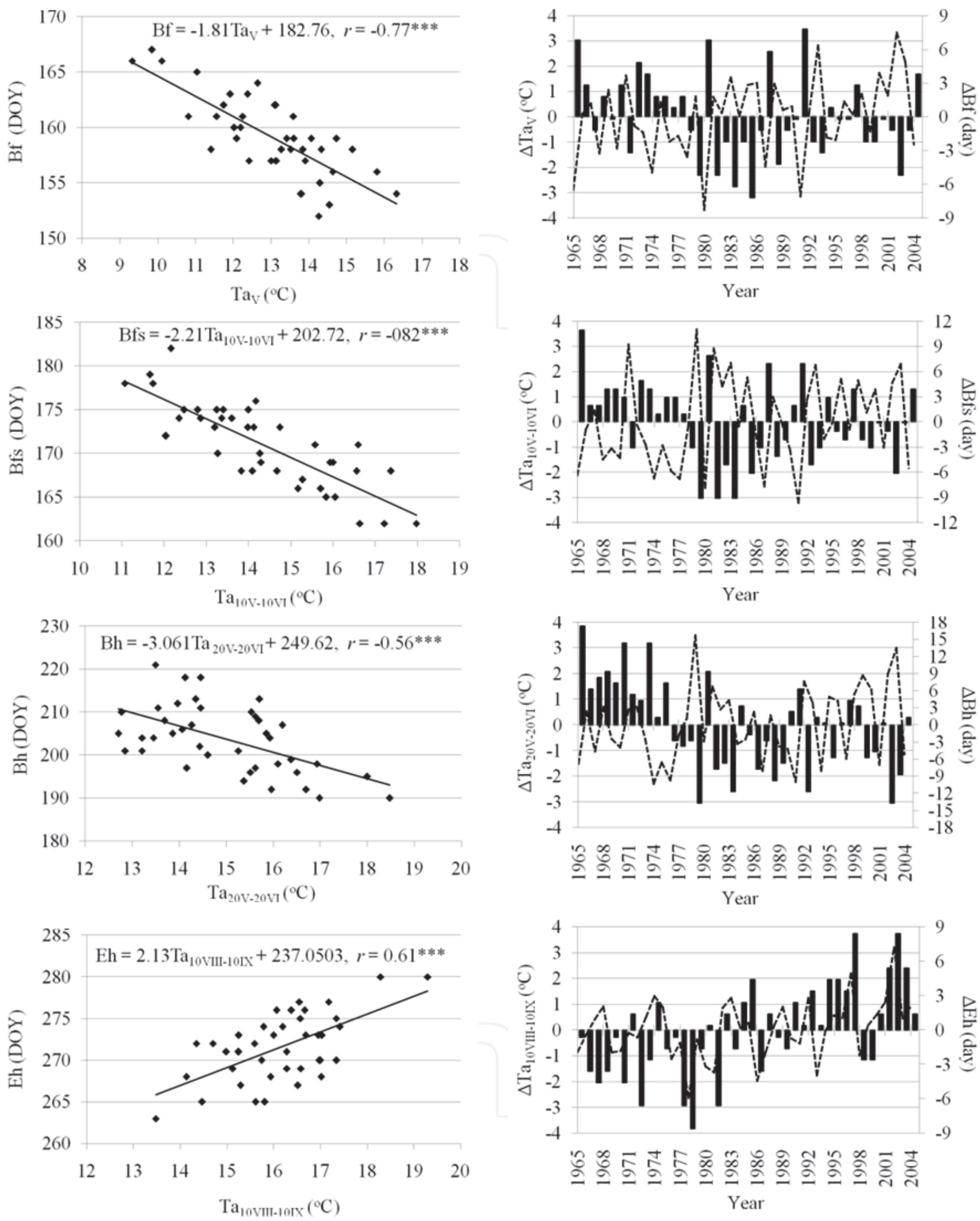
Regression equations	Characteristics						
	t	*F*	*r*	*S-Sy* (day)	*ARFE* (%)	frequency of the occurrence of |*RFE*| in range	
	bx / *a*					0-2 (%)	2-4 (%)
$Bf = -1.81Ta_V + 182.76$	-7.5 / 57.7	56.3	-0.77***	1.4	1.4	77.5	22.5
$Bfs = -2.21Ta_{10V-10VI} + 202.72$	-8.4 / 55.3	75.3	-0.82***	2.1	1.2	82.5	17.5
$Bh = -3.061Ta_{20V-20VI} + 249.62$	-4.2 / 22.5	17.6	-0.56***	0.8	2.6	40.0	37.5
$Eh = 2.13Ta_{10VIII-10IX} + 237.0503$	4.8 / 32.6	22.8	0.61***	1.3	1.8	75.0	25.0

t – value of the *t*-Student test, *F* - value of the *F*-Snedecor test, *r* – correlation coefficient, *S-Sy* - difference between a standard deviation of a dependent variable and a standard error of equation estimation (day), *ARFE* - average relative forecast error (%), *RFE* - relative forecast error (%), *bx* – regression coefficient, *a* – intercept, Ta - average air temperature (^oC). The remaining explanations see Table 2.

Table 4. Regression analysis describing the relationship between the agrotechnical date (Bh, Eh) and the date of the phenological phase (Bf, Bfs) of tomato and average air temperature in Poland in the years 1965-2004.

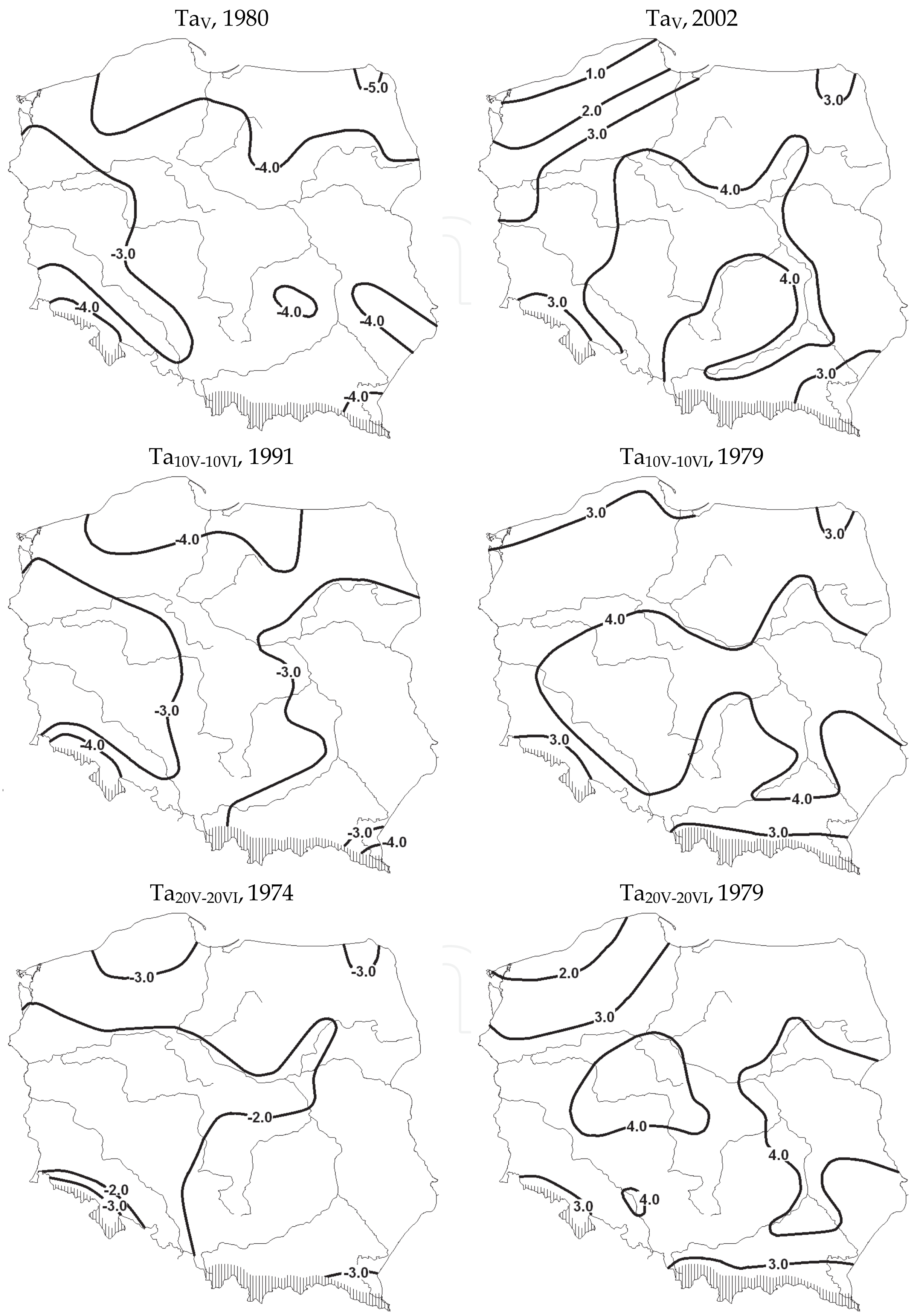
In 2002, the highest air temperature in May (Ta_V) was recorded, 3.3^oC higher than the average (Fig. 9). In 2002, the date of the beginning of tomato flowering was earlier than the average in the years 1965-2004, by about 5 days. In the period from 10^{th} May to 10^{th} June ($Ta_{10V-10VI}$), air temperature was highest in 1979 (3.7^oC higher than the average). Also in 1979, the air temperature was the highest (3.5°C higher than the average) in the period from 20th May to 20th June ($Ta_{20V-20VI}$). In the period 10th August to 10th September ($Ta_{10VIII-10IX}$), air temperature was highest in 2002 (3.2°C higher than the average), i.e. like in May. Air temperature in 1979 was higher than the average 1965-2004 air temperature. The higher 1979 air temperature contributed to acceleration of the dates of the beginning of fruit-setting and the beginning of harvesting, respectively by about 9 and 14 days compared to the average date. On the other hand, above-average temperatures in 2002 contributed to about an 8 days delay in the end of harvesting date.

In May, in extreme years in terms of the course of thermal conditions of air, spatial distribution of air temperature was considerably different from the multi-annual structure in the years 1965-2004 (Fig. 10). In 1980 deviations from the norm of the analysed meteorological element, varied in most regions of Poland from -3.0 to -5.0°C, and in 2002 from 1.0 to 4.0°C. In 1980, it was coldest in the north-eastern part of the country and warmest in the central-west. In 2002, the lowest, positive air temperature which deviated from the average, were recorded in the north-west. The highest air temperatures which deviated from the average, were recorded mostly in central and southern Poland. In the periods from 10th May to 10th June in 1991 and 1979, the structures of air temperature deviating from the norm in Poland, were different than in May. In 1991 negative deviations oscillated from above -3.0°C in the central-western and central-eastern parts of the country to below -4.0°C in the northern, south-western and south-eastern parts. In 1979, as opposed to 1991, the highest deviations from the norm, amounting to above 4.0°C, were recorded in the central strip of Poland, stretching in latitude to the eastern border of the country. In the period from 20th May to 20th June, in the years of the highest deviations from the average, air temperature deviation oscillated from below -3.0°C in 1974 to above 4.0°C in 1979 (Fig. 9). In summer, in the period from 10th August to 10th September, the values of temperature deviations from the norm were similar to the earlier characterised periods and they oscillated generally from -3.0°C in 1978 to 4.0°C in 2002. In the summer of 1978, the air temperature was 3.0°C lower than the multi-annual average. This 3.0°C lower temperature occurred mainly in north and south-east Poland (Fig. 10). In the warmest period from 10th August to 10th September, which was recorded in 2002, in the central part of the country, on the Bay of Gdańsk and in the central-western part of Poland. This high 2002 temperature was 4.0°C higher than the average 1965-2004 temperature. In the tomato growing season, in the period from May to October, air temperature in the analysed years oscillated from 12.9 to 15.7°C, and at the stations of COBORU – as much as from 11.6 to 18.0°C. On the other hand, average air temperature during short periods, significantly influencing agrotechnical dates and the dates of phenological phases of tomato, oscillated from 13.0°C for Ta_V to 16.1°C for $Ta_{10VIII-10IX}$ (Table 5, Fig. 11). In May, the highest average air temperature amounted to 16.3°C, and was 1.7°C lower than the highest average $Ta_{10V-10VI}$, 2.2°C and 3.0°C lower, respectively, than the highest averages $Ta_{20V-20VI}$ and $Ta_{10VIII-10IX}$. The absolute maximum air temperature was from 8.0°C higher than the minimum one in the period from 10th August to 10th September, to 11.2°C in May. Average air temperature in Poland was marked by the highest variability in the period from 10th May to 10th June, which is confirmed by the value of standard deviation (S = 1.8°C). Temperature in the period from 10th August to 10th September was marked by the decidedly lowest variability. Temperature in the period from 10th August to 10th September had the lowest determined standard deviation (S = 1.1°C) and the smallest range (R = 5.8°C).



r – correlation coefficient, *** significant at $p \leq 0.01$.

Fig. 9. Left-hand side: relationship between agrotechnical dates (Bh, Eh) and phenological phases (Bf, Bfs) of tomato in Poland and average air temperature (Ta_V, $Ta_{10V\text{-}10VI}$, $Ta_{20V\text{-}20VI}$, $Ta_{10VIII\text{-}10IX}$). Right-hand side: deviations from the multi-annual average (1965-2004) in Poland of the dates (ΔBh, ΔEh) and phases (ΔBf, ΔBfs) of tomato and air temperature (ΔTa_V, $\Delta Ta_{10V\text{-}10VI}$, $\Delta Ta_{20V\text{-}20VI}$, $\Delta Ta_{10VIII\text{-}10IX}$) in the subsequent years of the analysed multi-annual period 1965-2004.


Ta_{V}, 1980
-5.0
-4.0
-3.0
-4.0
-4.0
-4.0
-4.0
Ta_{V}, 2002
1.0
2.0
3.0
3.0
4.0
4.0
3.0
3.0
$Ta_{10V-10VI}$, 1991
-4.0
-3.0
-3.0
-4.0
-3.0
-4.0
$Ta_{10V-10VI}$, 1979
3.0
3.0
4.0
3.0
4.0
3.0
$Ta_{20V-20VI}$, 1974
-3.0
-3.0
-2.0
-2.0
-3.0
-3.0
$Ta_{20V-20VI}$, 1979
2.0
3.0
4.0
4.0
3.0
4.0
3.0

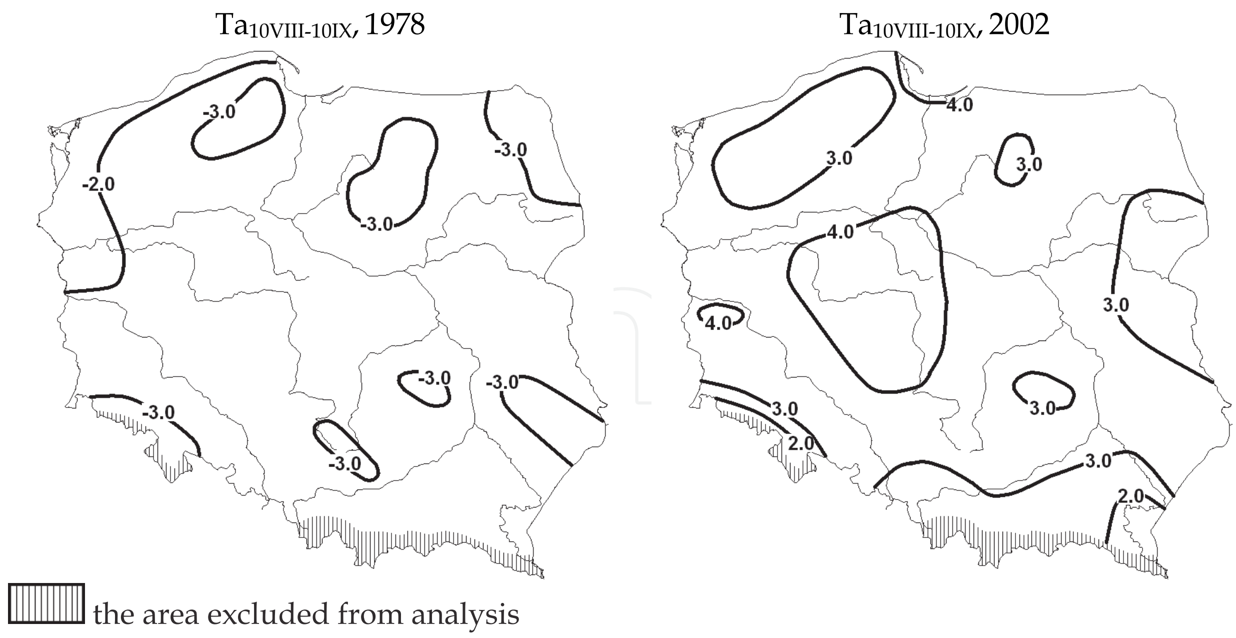


Fig. 10. Deviations from the multi-annual average (1965-2004) of air temperature in Poland: in May (Ta_V) – in 1980 and 2002, in the period 10th May-10th June ($Ta_{10V-10VI}$) – in 1979 and 1991, in the period 20th May-20th June ($Ta_{20V-20VI}$) – in 1974 and 1979 and in the period 10th August-10th September ($Ta_{10VIII-10IX}$) – in 1978 and 2002.

In the whole growing season of tomato, a significant increase in air temperature by 0.3°C /10 years ($p \leq 0.05$) was proved. Out of the four short analysed periods, there was a significant increase only in two air temperatures, most in May by 0.4°C/10 years ($p \leq 0.01$), and slightly less in the period from 10th August to 10th September by 0.3°C /10 years ($p \leq 0.01$). In Poland, air temperature increase was not uniform in all climatic regions (Fig. 12). The changes of agrotechnical dates and tomato development stages were also not uniform in all climatic regions (Fig. 2, Fig. 6). In May, a significant increase in air temperature, by more than 0.5°C /10 years, was recorded in the western part of Poland. The highest increase in air temperature was in the Kraków and Wrocław regions where air temperature increased by as much as 0.6°C /10 years. In summer, in the period from 10th August to 10th September a significant increase of more than 0.4°C /10 years, occurred in the south-west and locally in the central-west and the north. The highest increase of 0.5°C /10 years was in the Wrocław region.

4. Discussion

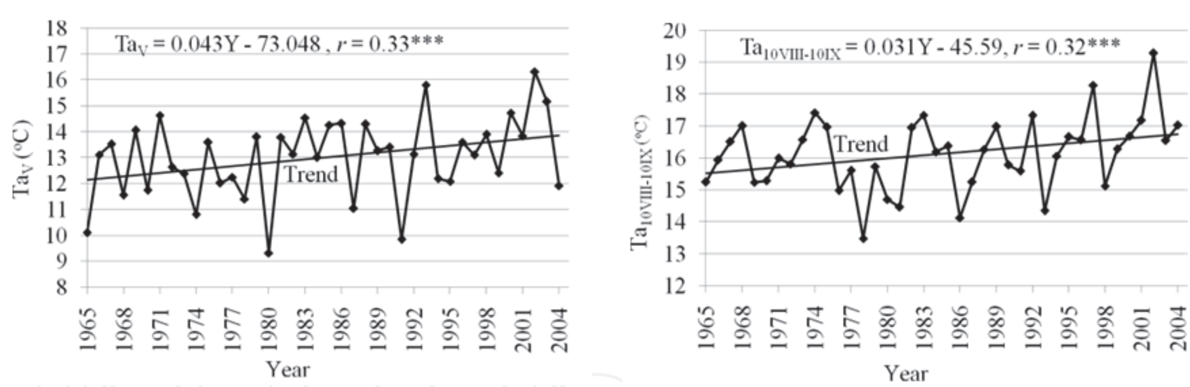
Since the second half of the 20th century in many places of Europe, changes of average phenological dates have been observed in both the world of wild-growing and crop plants (Ahas et al., 2002; Bonofiglio et al., 2009; Chmielewski et al., 2004; Menzel, 2000; Menzel & Estrella, 2001). The most frequently shown direction of change has been in the acceleration of phenological dates, especially in relation to spring and summer dates. The strongest acceleration of phenological dates has been observed since the end of the 1980s (Kalbarczyk, 2009a; Kalvāne et al., 2009; Schleip et al., 2009a). However, the size and direction of the changes of phenological dates is spatially diverse. In many research studies, acceleration of phenological dates has been confirmed mainly in the north-western part of the Europe, but

Period	Temperature (°C)						Absolute temperature (°C)	
	mean	highest	lowest	range⁴	S	trend (°C/10a)	max	min
May	13.0	16.3	9.3	7.0	1.5	0.4***	18.7	7.5
10th May-10th June	14.3	18.0	11.1	6.9	1.8	n.s.	19.7	9.2
20th May-20th June	15.0	18.5	12.7	5.8	1.4	n.s.	21.3	10.6
10th August-10th September	16.1	19.3	13.5	5.8	1.1	0.3***	20.5	12.5
May-October	14.3	15.7	12.9	2.8	0.7	0.3**	18.0	11.6

max – absolute maximum temperature, min – absolute minimum temperature, [4]between the highest and the lowest temperature. The remaining explanations see Tables 2 and 3.

Table 5. Statistical characteristics of the average air temperature in the growing season (May-October) of tomato, and in the periods significantly affecting agrotechnical dates and the dates of phenological phases in Poland, in the years 1965-2004.

also in Central Europe, in the Black Sea region, in the Baltic Sea region and around the Carpathians (Estrella et al., 2007; Kalvāne et al., 2009; Menzel & Estrella, 2001; Mozny et al., 2009). Delay of phenological dates according to Schleip et al. (2009a) has been observed in central Poland and in the Baltic Sea region. Delay of phenological dates, proved by research, mainly pertains to the autumn period, but in this case the direction of change is diverse, depending on the examined plant species (Gordo & Sanz, 2009).



r – correlation coefficient, *** significant at $p \leq 0.01$.

Fig. 11. Temporal distribution of the average air temperature in May (Ta_V) and in the period 10th August-10th September ($Ta_{10VIII-10IX}$) in Poland, in the subsequent years of the analysed multi-annual period 1965-2004.

The observed changes most often oscillate from 1 to several days per 10 years, and less frequently – about a dozen days per 10 years (Fujisawa & Kobayashi, 2010; Tao et al., 2006). Acceleration of hop flowering observed in the Czech Republic amounted to -1.6 days/10 years (Mozny et al., 2009). In Germany changes of certain phenological dates of winter rye and fruit trees amounted to -2.0 to -2.9 days/10 years (Chmielewski et al., 2004). According to Estrella et al. (2007) in the multi-annual period 1951-2004, average acceleration of phenological dates of field plants and vegetables in Germany amounted to -1.1 to -1.3 days /10 years. In the Mediterranean region, changes of leaf unfolding, flowering and fruiting which had been measured since the mid-70s amounted to -3.2 to -5.9 days /10 years (Gordo & Sanz, 2009). A much bigger acceleration occurred in the case of wild-growing trees; in Lithuania and Latvia, European hazel flowering was accelerated by -1 to -11 days /10 years and alder bloomed earlier from -1 to -15 days /10 years (Kalvāne et al., 2009).

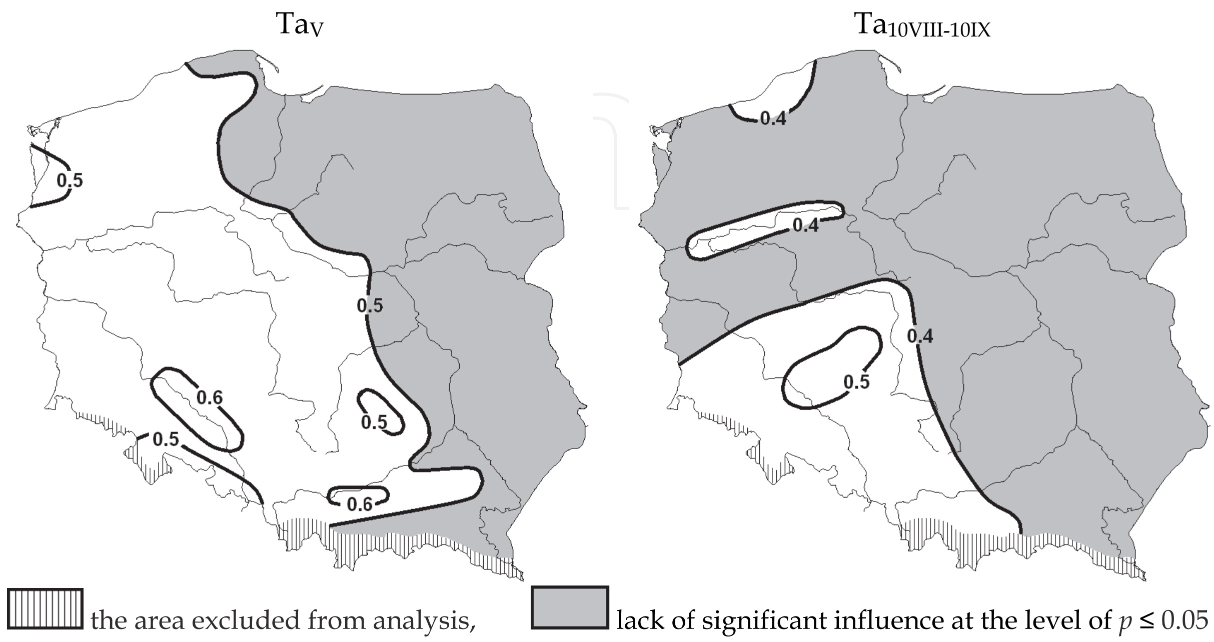


Fig. 12. Statistically significant, at least at the level of $p \leq 0.05$, linear regression coefficients for the trend of the average air temperature in May (Ta_V) and in the period 10th August-10th September ($Ta_{10VIII-10IX}$) in Poland, calculated for 10 years, in the years 1965-2004.

During the 40-year period of the present research, there was an acceleration of almost all phenological dates of tomato. This acceleration amounted to -0.6 to -3.5 days /10 years. The biggest acceleration concerned the dates occurring at the end of June and the beginning of July. Acceleration of dates of similar size was observed in Poland in relation to other vegetal and crop plants (Kalbarczyk, 2009a, 2009b). The results show that thermophilous vegetal plants cultivated in Poland are subjected to similar thermal conditions as plants cultivated in the western part of Europe. However, persistence of a negative trend for the tomato dates in June, over several years, can be evaluated as not very favourable. Cultivating tomatoes at too early a date is a risk because of the possibility of a late spring frost (Kalbarczyk, 2010b). In Poland the average date of occurrence of the last spring frost is marked by a negative trend (Koźmiński et al., 2010). However, such a trend was not confirmed for the absolute dates of frost occurrence. In Poland, the last spring frost may occur even at the end of June.

The above-mentioned possible delay of autumn phenological dates (Gordo & Sanz, 2009; Matsumoto, 2010), in the case of tomato cultivated in Poland, manifests itself by delay of the end of harvesting. In the examined multi-annual period, the end of harvesting was delayed by 2 days /10 years. The proved later course of some dates can be found in the research conducted in Spain, Japan and China (Gordo & Sanz, 2009; Matsumoto, 2010; Matsumoto et al., 2003; Tao et al., 2006). The degree of the observed delay was within a range of from 3.6 to as much as 21 days /10 years.

Changes of the phenological dates cause diverse duration of particular development stages of plants, and duration of the whole growing season (Liu et al., 2010; Moiseev et al., 2010; Mozny et al., 2009). According to research studies, the observed changes in duration of the growing period most frequently lead to lengthening, which can amount to about a dozen days (Kalvāne et al., 2009; Song et al., 2008). Lengthening of the growing period occurs in the case of an earlier beginning of spring and summer phenological dates and a later course of autumn phenophases. Lengthening of the growing season may even occur in the case of acceleration of all phenological dates. In the Baltic states, the growing season lengthened in spite of the recorded acceleration of both spring and autumn dates (Kalvāne et al., 2009). This lengthening was a consequence of a big dominance of spring acceleration over autumn acceleration. In the 31-year research period, the growing season of wild-growing trees in Lithuania and Latvia lengthened by 7 days (Kalvāne et al., 2009). Lengthening of the growing season by 8% (18 days) was also confirmed in the Mediterranean region (Gordo & Sanz, 2009). The cause of this lengthening was also mainly the acceleration of the spring phases.

The duration of the particular developmental stages of plants underwent more diverse changes. A year by year shortening in the duration of the spring and summer development stages is observed most frequently. However, extreme differences occur which depend on: development stage, kind of plant, and the area of its cultivation or occurrence. In Germany, significant shortening of the period from sowing to emergence of maize was found to be, on average 1.6 days/10 years (Chmielewski et al., 2004). However, duration of the remaining part of maize growth and development, i.e. from emergence to the beginning of harvesting, lengthened, on average, 2.1 days/10 years. Significant lengthening of development stages was also proved for the period from the beginning of stem elongation to the beginning of heading of winter rye, and the beginning of row closing to the beginning of harvest of sugar beet. The degree of lengthening amounted to 1.0 day/10 years for winter rye and 1.2 days/10 years for sugar beet (Chmielewski et al., 2004). In Poland, negative trends in the duration of some development stages were proved for, e.g., onion, medium-early potato and medium-late potato (Kalbarczyk, 2009b, Kalbarczyk E. & Kalbarczyk R., 2010). A significant shortening of duration for two onion periods was also proved. For the period from sowing to the end of emergence, shortening amounted to -1.7 day/10 years; for the period from the end of emergence to the beginning of leaf bending it amounted to -0.7 day/10 years. Similar results were obtained for potato. Medium-late potato cultivars were characterised by a shortening of the period from emergence to flowering by -1.7 days/10 years. For medium-early potato cultivars, shortening of the period from haulm drying to harvesting was -0.8 day/10 years. On the other hand, for both groups of potatoes, the period from flowering to haulm drying lengthened by about 2-3 days/10 years (Kalbarczyk E. & Kalbarczyk R., 2010). In the case of tomato, in the years 1965-2004, only the period Bfs-Bh became significantly shorter; on average by -1.4 days/10 years. However, an opposite tendency was seen in the case of the period from the beginning of harvesting to the end of harvesting of the plant. The period from the beginning of harvesting to the end of harvesting, on average, lengthened by as much as 5.6 days/10 years. Changes in the duration of particular tomato development stages caused the whole season, which lasts from planting up to the end of harvesting, to lengthen by 2.6 days/10 years. It seems that a longer period of tomato harvesting creates the possibility of achieving a bigger yield of the plant.

The conducted research confirmed that, in the case of tomato, like the majority of plants (Craufurd & Wheeler, 2009; Morin et al., 2010; Schliep et al., 2009b), changes in the course of tomato phenological dates and in duration of tomato development stages are significantly dependent on changes in air temperature. The relationship between tomato growth and

development and temperature was confirmed in the research by Bojacá et al. (2009) and van der Ploeg & Heuvelink (2005). All phenological and agrotechnical dates of tomato considered in the present study, were significantly dependent on air temperature. The first three dates: Bf, Bfs, Bh, were negatively correlated with air temperature, and the last considered date, Eh, was positively correlated with air temperature. The degree of change in the tomato phenological date, caused by a 1°C temperature change, amounted to 1.8 to 3.1 days. Similar reactions were observed in other crop plants in Poland and Germany (Chmielewski et al., 2004; Kalbarczyk E. & Kalbarczyk R., 2010). A statistically confirmed air temperature increase in May and in the period from 10th August to 10th September amounted to, respectively, 0.4°C/10 years and 0.3°C/10 years. In southern Poland, the temperature trend in May amounted to as much as 0.6°C/10 years. The obtained results are similar to those described in different parts of Europe (Bauer et al., 2009; Bonofiglio et al., 2009; Chmielewskiet et al., 2004; Kapur et al., 2007; Saue & Kadaja, 2010) and the world (Lobell et al., 2007; Song et al., 2008; Wang et al., 2008).
Air temperature may affect the quantity and quality of the yield directly and indirectly (Tshiala & Olwoch, 2010). Indirect influence of air temperature is seen through the proven effect on the rate of growth and development of plants. The present work confirms changes occurring in the course of tomato development in Poland. However, there are no clear observations corroborating an increase or decrease in tomato yield occurring from this cause.

5. Conclusions

An increase, by 0.3°C /10 years, in average air temperature in the growing season of tomato (May-October), contributed to the changes of not only the dates of phenological phases and development stages but also to the agrotechnical dates of the plant. In the years 1965-2004, important changes in temporal distribution of all the considered dates were noted, and of the period duration from planting up to the end of harvesting. In Poland, the growing season of field-cultivated tomato lengthened by 2.6 days /10 years, which resulted both from acceleration of the dates of: planting up (-0.6 day /10 years), flowering (-0.7 days /10 years), fruit-setting (-1.1 days /10 years), the beginning of harvesting (-3.5 days /10 years), and delay of the end of harvesting date (2.1 days /10 years). The biggest changes in the development of the tomato were recorded in the fruiting period - from the beginning to the end of harvesting, which for the whole country, on average, lengthened by 5.6 days / 10 years. However, in Poland this lengthening was not even, as it fluctuated from less than 1.5 days /10 years in the northern, north-eastern and central-eastern parts of the country, to above 2.5 days /10 years in the southern part.
An increase, by 1°C, in the average air temperature during the periods which significantly affect the dates of tomato caused acceleration of: the beginning of flowering by 1.8 days, the beginning of fruit-setting by 2.2 days, the beginning of harvesting by 3.1 days and delay of the end of harvesting by 2.1 days. During the 1965-2004, 40-year research period, deviations from the multi-annual average of the agrotechnical dates and duration of tomato development stages were discovered. These deviations were a result of the change in thermal air conditions. The date of the beginning of harvesting differed most from the average date in 1965, and the date of the end harvesting differed most from the average date, in the years: 1978, 1997 and 2002. Positive deviations from the norm of agrotechnical dates in Poland, oscillated from less than 4 to more than 8 days, in the years 1965 and 2002,

and from less than 2 to more than 6 days in 1997. Negative deviations from the norm of agrotechnical dates in Poland, oscillated from more than 6 to less than 8 days, in 1978. The length of the period from the beginning of harvesting to the end of harvesting differed most from the multi-annual average in 2002, and the length of the period from planting up to the end of harvesting in 1978 and 2002. The highest deviation from the norm, for the duration of the period from the beginning to the end of harvesting, amounted to more than 14 days, and occurred in the central-west and in the Warsaw region.
Changes in the course of tomato development found in the present work do not lead to evident changes in cropping of this plant. However many things indicate, that the occurring changes may improve the conditions of tomato field-cultivation in Poland, in the future. According to the IPCC report (2007), it is predicted that as a result of climate change the yield of crop plants in central Poland will decrease on average by 5%. On the other hand, there are forecasts of an increase in the yield in the north by 5% and by 30% in the submontaineous regions. The changes in the yield quantity will vary depending on a type of plants. The highest yield increase, by several dozen per cent, is predicted for thermophilous plants, which will result from increased thermal resources.

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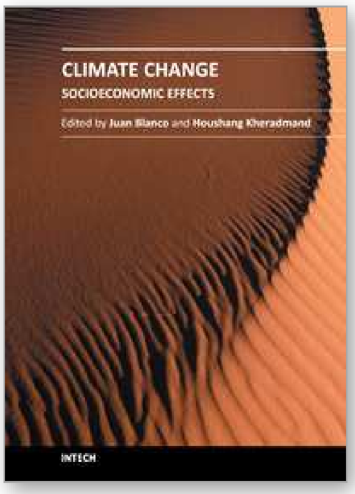

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This book shows some of the socio-economic impacts of climate change according to different estimates of the current or estimated global warming. A series of scientific and experimental research projects explore the impacts of climate change and browse the techniques to evaluate the related impacts. These 23 chapters provide a good overview of the different changes impacts that already have been detected in several regions of the world. They are part of an introduction to the researches being done around the globe in connection with this topic. However, climate change is not just an academic issue important only to scientists and environmentalists; it also has direct implications on various ecosystems and technologies.