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SPATIAL AND TEMPORAL VARIABILITY OF THE OCCURRENCE OF GROUND FROST IN POLAND AND ITS EFFECT ON GROWTH, DEVELOPMENT AND YIELD OF PICKLING CUCUMBER (*Cucumis sativus* L.), 1966–2005

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Abstract. In the world of plants frost is a particularly dangerous phenomenon. Destructive effect of frost on plants is both direct and secondary. The amount of damage done by frost depends on its intensity, frequency, a season of its occurrence and a plant species. The aim of the work was to find spatial and temporal distribution of ground frost in Poland and to determine effect of minimum air temperature at the ground level on the dates of phenological phases and harvesting and duration of development stages and also on the quantity of cucumber yield of pickling cultivars at the turn of the 20th and 21st centuries. Source materials used in the present study were collected from 28 experimental stations of COBORU and from 51 meteorological stations of IMGW in the years 1966–2005. Ground frost was characterised, e.g., by means of average dates of last spring and first autumn frost, duration of the period without frost and also intensity and frequency of its occurrence and a linear trend. Effect of minimum air temperature at the ground level on the growth, development and crop productivity of cucumber was determined with the use of linear and curvilinear regression analysis and the linear trend of occurrence of last spring and first autumn frost and duration of the period without frost with the use of linear regression analysis. Ground frost poses high potential risk for field cultivation of cucumber in Poland not only because of the fact that it significantly determines the rate of growth, development and yield quantity of the plant but also because of its high spatial and temporal variability; the highest cultivation risk occurs in north-eastern Poland where significant shortening, year by year, of the period without frost was proved and where the highest frequency of frost occurrence both at the beginning and at the end of the cucumber growing season is recorded.

Key words: cucumber, air temperature at the ground level, temporal trend, development stage, regression analysis

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INTRODUCTION

Air temperature at the ground level is a very important meteorological factor which regulates the rate of life processes of plants and chemical reactions in their surroundings and which is marked by unusually high variability in time and space [Koźmiński and Trzeciak 1971, Brázdil et al. 1995, Peck 1996, Lindkvist and Lindqvist 1997, Dragańska et al. 2004, Kołodziej et al. 2004, Kalbarczyk 2009a, 2009b]. What is of importance to plants is extreme temperatures – minimum and maximum temperatures and their distribution in time because these two extremes constitute limits of life within which particular plant species may exist [Fletcher and Moot 2006, Grabowski et al. 2007, Loginov et al. 2007, Maqbool et al. 2009]. Considerable shortage or excess of this factor can even cause dying of plants and air temperature determines all life processes of plants: photosynthesis, respiration, transpiration and growth [Krug and Thiel 1985, Lederle and Krug 1985, Liebig 1985, Marcelis and Hofman-Eijer 1993, Yoshida et al. 1998, Akinci and Abak 1999, Medany et al. 1999].

In the world of plants frost is a particularly dangerous phenomenon [Koźmiński and Michalska 2001, Wilczyński et al. 2005]. Destructive effect of frost on plants is both direct and secondary [Koźmiński and Trzeciak 1971]. The amount of damage done by frost depends on its intensity, frequency, a season of its occurrence and a plant species [Koźmiński 1976, Dragańska et al. 2004, Gołaszewski 2004, Cittadini et al. 2006, Eccel et al. 2009, Feliksik and Wilczyński 2009].

The previous research dedicated to ground frost in Poland usually concerned only some geographical regions or even only surroundings of single meteorological stations and when it pertained to the whole country it was often based on distant in time, multiannual periods which do not cover significant changes in air temperature occurring at the turn of the 20th and 21st centuries [Koźmiński and Trzeciak 1971, Koźmiński and Michalska 2001, Gołaszewski 2004, Kołodziej et al. 2004]. Also, there are few research studies dedicated to the assessment of effect of frost on the development and yield of crop plants; there are no studies on cucumber. Therefore, the aim of the work was to analyse occurrence of ground frost in Poland in the years 1966–2005 and its effect on the growth, development and crop productivity of cucumber.

MATERIAL AND METHODS

The analysis, as starting materials, used a 40-year series (1966–2005) of meteorological observations collected for 51 stations of the Institute of Meteorology and Water Management (fig. 1). The data used in the present study can be regarded as representative of almost whole Poland as their distribution is quite even and enables fairly exact description of frost occurrence variability, excluding the south-western and south-eastern parts of the country. Because of that, but also due to very high diversity of physiographical conditions in these parts of Poland, and, moreover, because of the fact that field cultivation usually occurs up to the height of 500 m above sea level they were excluded from the study (fig. 1). Measurements of the minimum air temperature, amounting to ≤0°C, conducted at the ground level, i.e. at the height of 5 cm, were used to determine dates of occurrence of last spring and first autumn frost and also to determine frequency of their occurrence in the growing season of cucumber (from May to September) and duration of periods without frost. The work also determined intensity of frost according to the following temperature ranges: from 0 to -2°C (mild frost), from -2.1 to -4°C (moderate), from -4.1 to -6°C (severe) and below -6°C (very severe) at the beginning (in May) and at the end (in September) of the cucumber growing season for each of the 51 analysed IMGW stations. The same ranges of frost intensity were accepted, among others, by: Díaz and Martínez [1993] and Dragańska et al. [2004].

Fig. 1. Location of meteorological stations of IMGW (●) and experimental stations of COBORU (□) used in the study

Ryc. 1. Lokalizacja stacji meteorologicznych IMGW (●) i stacji doświadczalnych COBORU (□), które zostały wykorzystane w opracowaniu

The work also used data concerning growth, development and crop productivity of cucumber and agrotechnical dates collected from 28 experimental stations of COBORU in the successive years of the considered multi-annual period 1966–2005, except for 2003 and 2004, when field experiments on this plant were not carried out (fig. 1). The COBORU experimental data were collected for all the most common in cultivation varieties of pickling cucumber examined in a given year which after averaging were accepted as a collective standard of the described plant. Effect of ground frost and minimum air temperature at the ground level on dates of phenological phases (the end of emergence, the beginning of flowering, the beginning of fruit-setting), agrotechnical dates (the beginning of harvesting, the end of harvesting), duration of development stages (sowing – the end of emergence, the end of emergence – the beginning of flowering, the beginning of flowering – the beginning of fruit-setting, the beginning of fruit-setting – the beginning of harvesting, the beginning of harvesting – the end of harvesting) and the quantity of yield (total, marketable) of cucumber were assessed on the basis of linear and curvilinear (2nd degree polynomial) regression analysis. In the regression equation, dates, periods and cucumber yield were dependent variables and the number of days with ground frost (Tfd) or the minimum air temperature at the ground level (Tfmin) and a linear trend, i.e. the successive years of the analysed multi-annual period 1966–2005 constituted independent variables. Significance of structural parameters of multiple regression and significance of the whole equation were assessed respectively on the basis of the *t*-Student test and the *F*-Snedecor test, and fitting of empirical data to the regression function line on the basis of the determination coefficient (R^2) [Dobosz 2001].

RESULTS

Spatial variability of frost occurrence

In Poland, in the years 1966–2005, spatial distribution of average dates of last spring ground frost was moderately diverse as the difference between extreme dates amounted, on average, to two weeks – most frequently from 10th to 25th May (fig. 2a). Earliest, till 10th May, last spring frost subsided in the region of the Szczecin Lagoon and the Bay of Gdańsk, also in the Kraków–Częstochowa Upland and in the region of Zielona Góra, and latest even after 25th May – in the Pomeranian Lakeland and also in the north-eastern, south-western and south eastern parts of the country. In central Poland average dates of last spring frost fell, on average, between 15th and 20th May and in the region of Siedlce, Leszno and in the Lublin Polesie after 20th May and in the south (the Silesian Upland, the Nida Basin, the Wielkopolska Lowland) – between 10th and 15th May. First dates of autumn frost were marked by considerably higher spatial variability than the dates of last spring frost as in Poland, on average, they took place from 15th September to 10th October (fig. 2b). Earliest, before 15th September, ground frost was recorded in the Podlasie Lowland and before 20th September in the north-east, the Lublin Upland, the Kaszuby Lakeland and also in the south-west and south-east. A lot later, before 10th October, autumn frost was recorded in the north – along the western coast of the Baltic and the Bay of Gdańsk. On average between 25th and 30th September autumn frost occurred in the Gorzów Plain, the Tuchola Forest and the Iława Lakeland and between 30th September and 5th October in the Wielkopolska Lakeland, the Wielkopolska Lowland, the Silesian Lowland, the Silesian Upland, the Sandomierz Basin and the western part of the Mazovian Lowland.

Apart from learning about distribution of last spring and first autumn frost, knowledge of distribution of average duration of the period without frost in different regions of Poland is also of big importance while determining the risk of cucumber growth and development. In Poland, in the years 1966–2005, the number of days without frost, determined between average occurrence dates of last spring and first autumn frost, oscillated between below 120 and above 150 days (fig. 2c). The longest period without frost, lasting over 150 days, was recorded along the Szczecin Lagoon and the Bay of Gdańsk and the shortest one, below 120 days, in the north-east, in Roztocze and submontainous regions – the Sudeten Foothills and the Carpathian Foothills. In most regions of northern and eastern Poland, in the Pomeranian and Masurian Lakelands, in the Lublin Polesie and in the eastern part of the Mazovian Lowland the period without frost lasted from 120 to 130 days, in central Poland – from 130 to 140 days, and in central and southern Poland stretching from Koło to Kraków through Kalisz, Częstochowa, Opole and Katowice, and also between Zielona Góra and Legnica and between Sandomierz and Przemyśl – above 140 days.

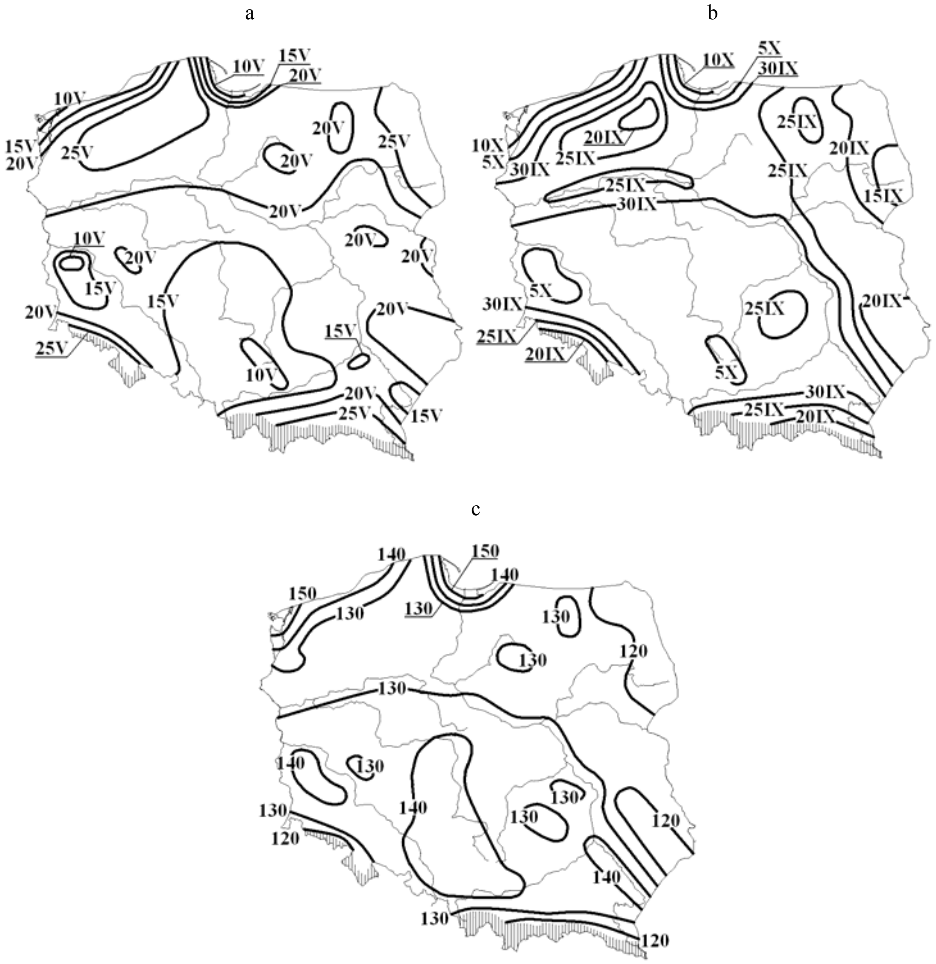


Fig. 2. Spatial distribution of average dates of ground frost – last spring frost (a) and first autumn frost (b) and average duration (expressed as days) of the period without frost (c) in Poland, 1966–2005

Ryc. 2. Przestrzenny rozkład średnich dat przymrozków przygruntowych – ostatnich wiosennych (a) i pierwszych jesiennych (b) oraz średnich długości (w dniach) okresu bezprzymrozkowego (c) w Polsce. Lata 1966–2005 a b

Fig. 3. Spatial variability of the range (expressed as days) of ground frost dates – last spring frost (a) and first autumn frost (b) in Poland, 1966–2005

Ryc. 3. Zmienność przestrzenna rozstępu (w dniach) dat przymrozków przygruntowych – ostatnich wiosennych (a) i pierwszych jesiennych (b) w Polsce. Lata 1966–2005

a b

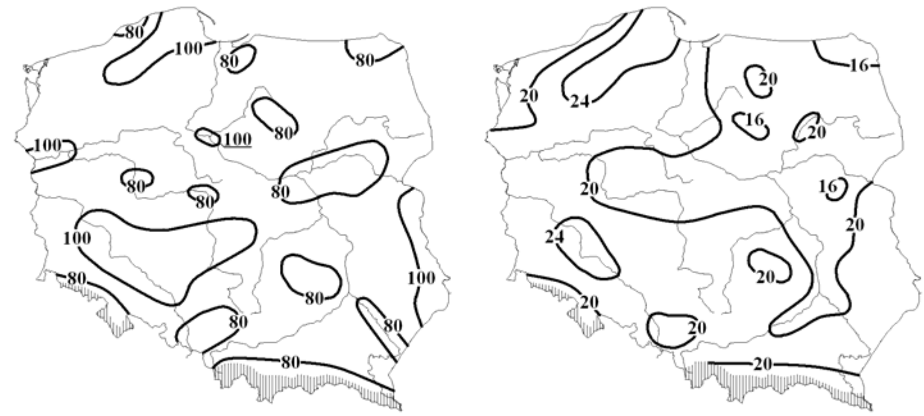


Fig. 4. Spatial variability of the nange (expressed as days, a) and standard deviation (expressed as days, b) of duration of the period without frost in Poland, 1966–2005

Ryc. 4. Zmienność przestrzenna rozstępu (w dniach, a) i odchylenia standardowego (w dniach, b) długości okresu bezprzymrozkowego w Polsce. Lata 1966–2005

The lowest variability of occurrence of dates of last spring frost described by means of a range was recorded in the region of Świnoujście and Ustka and in the central part of the Mazovian Lowland – the difference between the latest and the earliest date of the analysed phenomenon in the years 1966–2005 amounted to below 50 days, and the highest one, amounting to even above 70 days, occurred in Kaszuby, in the Pomeranian Lakeland, the Suwałki Lakeland, the Szczecin Lowland and the Opole Plain (fig. 3a). In the central strip of Poland, in the Małopolska Upland and the Sandomierz Basin the range between the dates of last spring frost oscillated between 50 and 60 days. Dates of first autumn frost were marked by higher variability because the range calculated for the considered phenomenon oscillated from 50 days in the north and in the regions of Kętrzyn and Koło to above 90 days in the central-west (the vicinity of Słubice and Gorzów Wielkopolski), in the Koszalin region, in the Silesian Lowland and in the south-east and also in the valley of the River Noteć and Vistula within the stretch between Piła and Płock (fig. 3b). The gap concerning duration of the period without frost oscillated from below 80 to above 100 days, and the biggest one was determined in Kaszuby and the Pomeranian Lakeland, the Silesian Lowland, the Piotrków Upland Plain, in the regions of Gorzów Wielkopolski and Toruń and the central-east (fig. 4a). A standard deviation was also calculated for the period without frost; in Poland most often it amounted to between 16 and 24 days, the lowest was in the Suwałki Lakeland and in the vicinity of Mława and Siedlce (fig. 4b).

Temporal trend of frost

In the examined multi-annual period 1966–2005 increasingly late occurrence of last spring frost was statistically proved at three stations: in Białystok (by +5.4 days/10 years, $P < 0.01$), Ostrołęka (by +5.8 days/10 years, $P < 0.01$) and in Suwałki (by +4.2 days/10 years, $P < 0.01$), situated in north-eastern Poland and increasingly early occurrence of the described phenomenon in: Katowice (by -4.1 days/10 years, $P < 0.05$), Kraków (by -8.1 days/10 years, $P < 0.01$) and Zielona Góra (by -7.1 days/10 years, $P < 0.01$) (fig. 5). On the other hand, at 8 meteorological stations, out of the 51 considered ones, a significant linear trend of the occurrence of first autumn frost was noted in the analysed multi-annual period, and in: Białystok, Kętrzyn, Ostrołęka, Terespol, Włodawa and Opole – a negative one, and in Szczecinek and Kraków – a positive one (fig. 6). The highest acceleration of first autumn frost was noted in Włodawa (by -6.1 days/10 years, $P < 0.01$), and next in Opole (by -4.3 days/10 years, $P < 0.01$), and the highest delay – in Szczecinek (by +5.1 days/10 years, $P < 0.05$). Significant changes in the occurrence of spring and autumn ground frost in the years 1966–2005 were not the only ones proved; changes were also proved in the case of duration of the period without frost (fig. 7). Significant lengthening of the period without frost was recorded at three stations located near each another in northern Poland (Szczecinek, Chojnice and Ustka) and at 3 stations situated in various regions of the country (Zielona Góra, Kalisz and Kraków), and significant shortening – at 5 stations of eastern Poland (Suwałki, Białystok, Ostrołęka, Terespol and Włodawa) and in Opole. Lengthening of the period without frost oscillated from +3.5 days/10 years ($P < 0.1$) in Ustka to +12.9 days/10 years ($P < 0.05$) in Kraków, and shortening – from -6.1/10 years ($P < 0.01$) in Suwałki to -10.0/10 years ($P < 0.01$) in Ostrołęka.

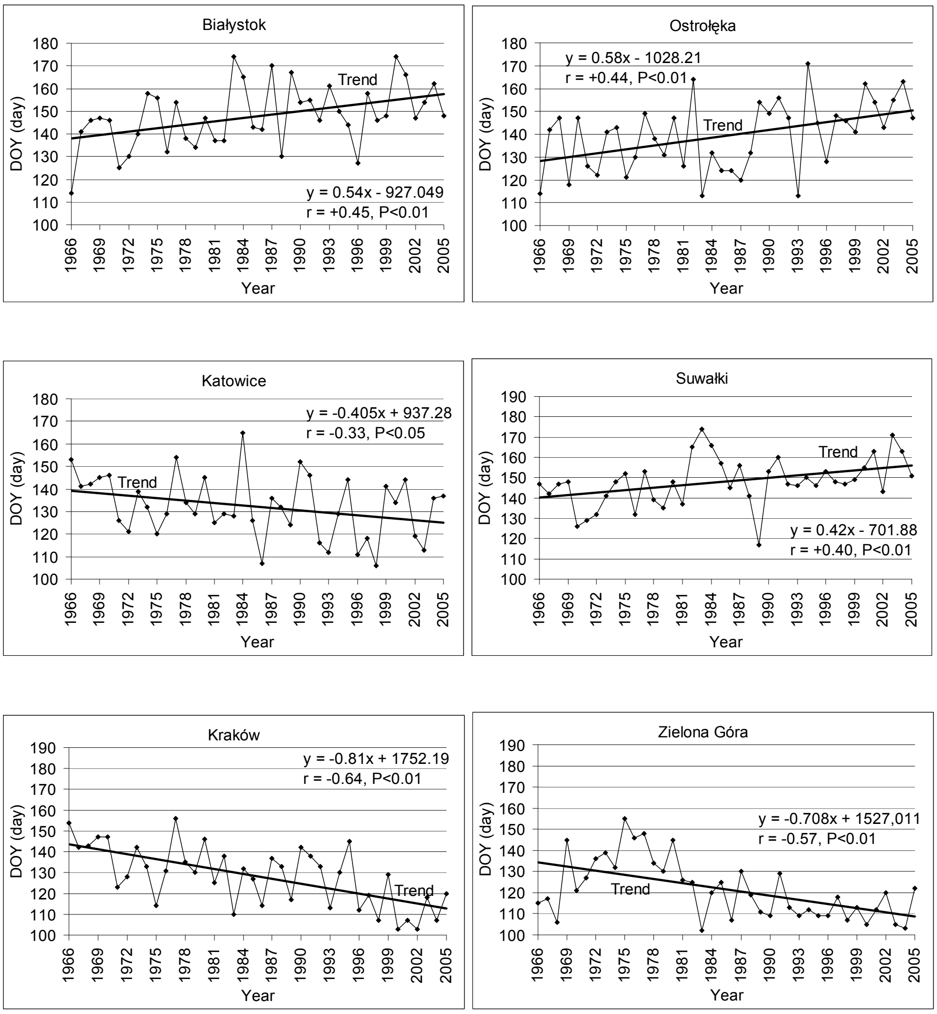


Fig. 5. Temporal distribution of occurrence of the dates of last spring ground frost in selected meteorological stations in Poland in the successive years of the multi-annual period 1966–2005. DOY – day of the year

Ryc. 5. Czasowy rozkład występowania dat ostatnich wiosennych przymrozków przygruntowych w wybranych stacjach meteorologicznych Polski, w kolejnych latach wielolecia 1966–2005. DOY – kolejny dzień roku

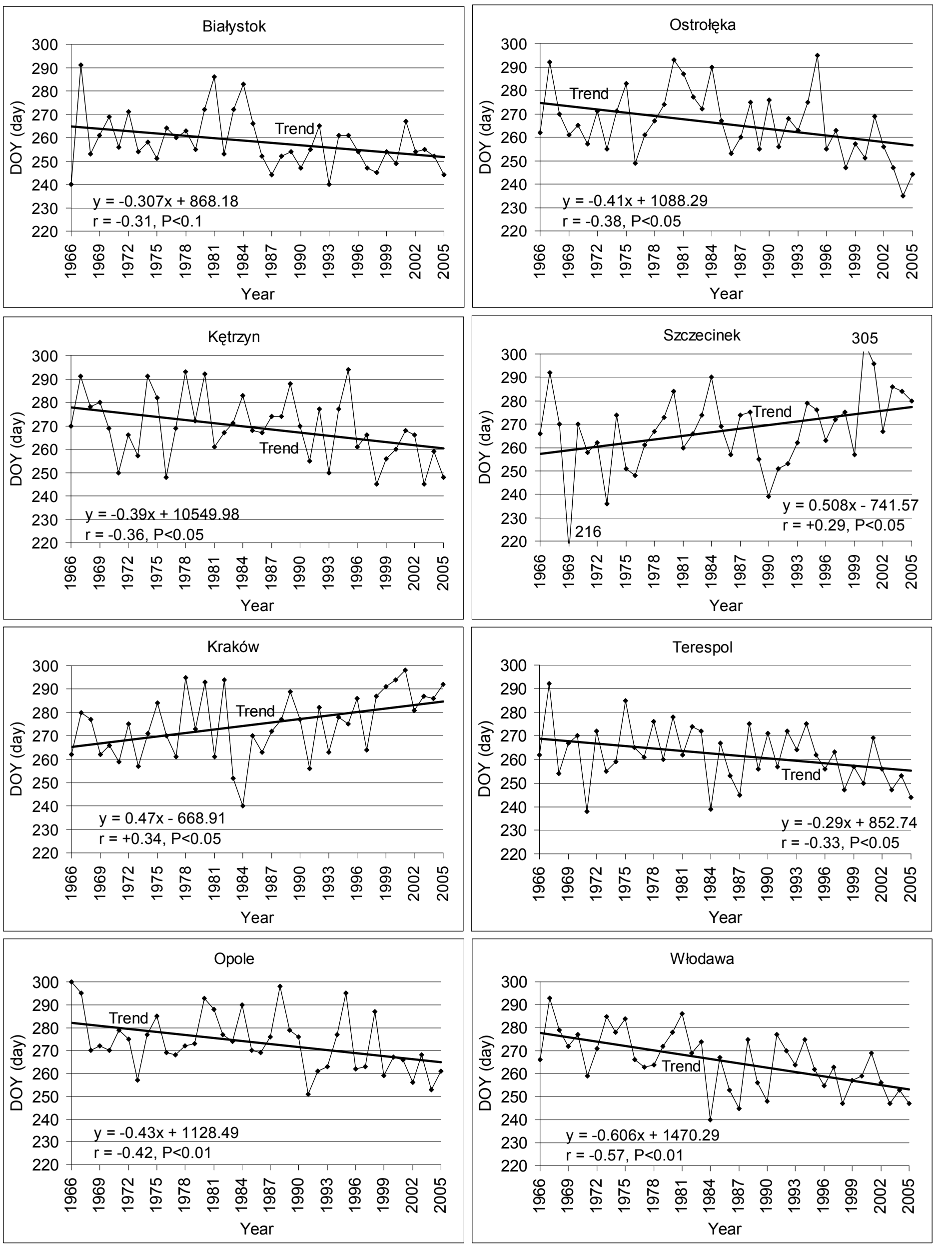
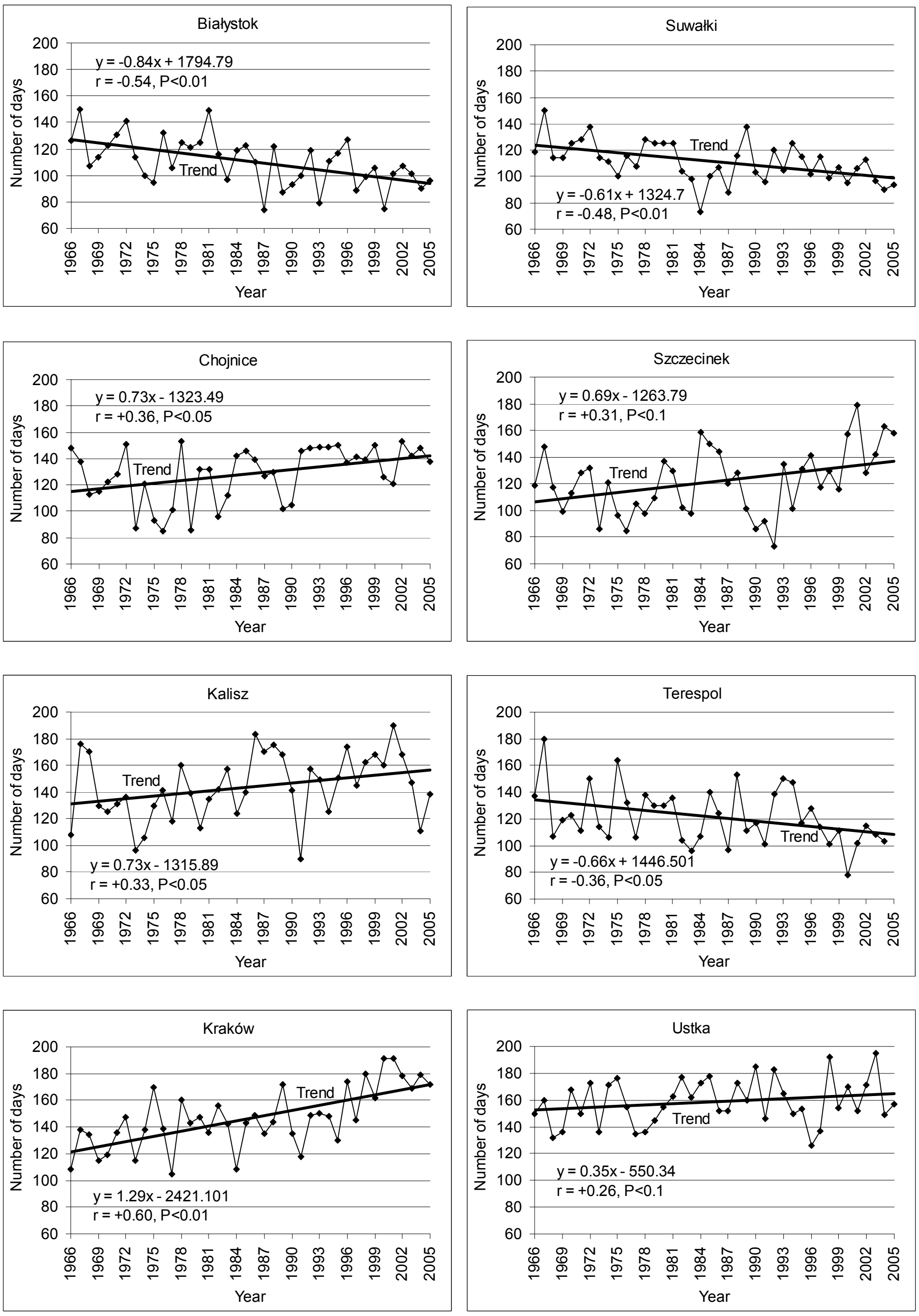


Fig. 6. Temporal distribution of occurrence of the dates of first autumn ground frost in selected meteorological stations in Poland in the successive years of the multi-annual period 1966–2005. DOY – day of the year

Ryc. 6. Czasowy rozkład występowania dat pierwszych jesiennych przymrozków przygruntowych w wybranych stacjach meteorologicznych Polski, w kolejnych latach wielolecia 1966–2005. DOY – kolejny dzień roku


Białystok
y = -0.84x + 1794.79
r = -0.54, P<0.01
Trend
Suwałki
y = -0.61x + 1324.7
r = -0.48, P<0.01
Trend
Chojnice
y = 0.73x - 1323.49
r = +0.36, P<0.05
Trend
Szczecinek
y = 0.69x - 1263.79
r = +0.31, P<0.1
Trend
Kalisz
y = 0.73x - 1315.89
r = +0.33, P<0.05
Trend
Terespol
y = -0.66x + 1446.501
r = -0.36, P<0.05
Trend
Kraków
y = 1.29x - 2421.101
r = +0.60, P<0.01
Trend
Ustka
y = 0.35x - 550.34
r = +0.26, P<0.1
Trend
Number of days
Year

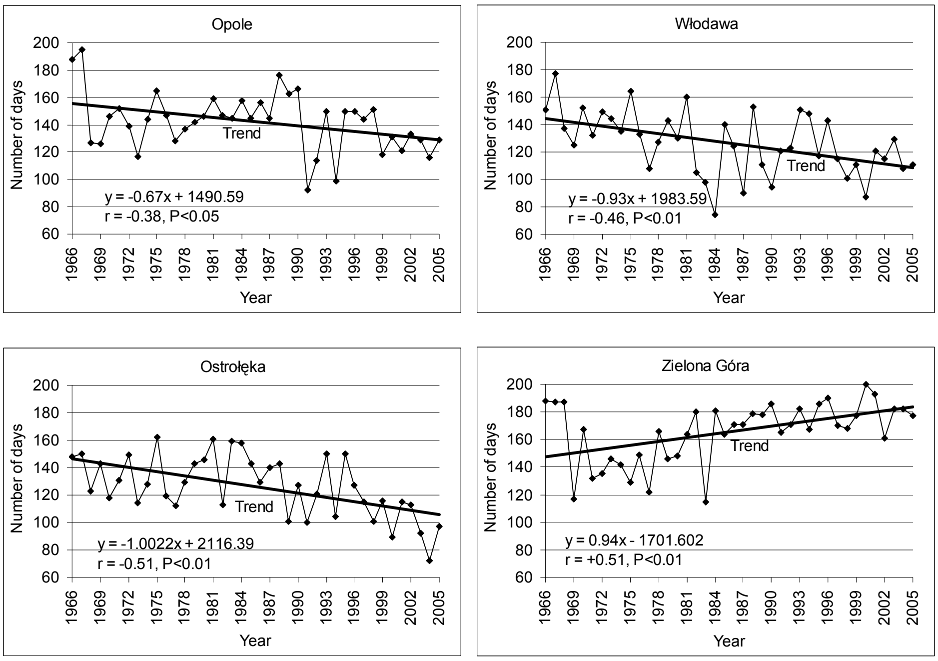


Fig. 7. Temporal distribution of duration of the period without frost in selected meteorological stations in Poland in the successive years of the multi-annual period 1966–2005

Ryc. 7. Czasowy rozkład długości okresu bezprzymrozkowego w wybranych stacjach meteorologicznych Polski, w kolejnych latach wielolecia 1966–2005

Frequency of frost occurrence

Spring ground frost after 30th April occurred most often, every 6–7 years, in the north-east, in the Pomeranian Lakeland (in the region of Lębork, Resko and Szczecinek), locally in the vicinity of Olsztyn, and also in the south-west and the south-east; least frequently, every 20 years, at the Szczecin Lagoon, in the vicinity of Zielona Góra and in the Sandomierz Basin (fig. 8a). North of the line running in the vicinity of the towns, Zielona Góra–Leszno–Kalisz–Koło–Ciechanów–Siedlce–Terespol, spring frost after 30th April in the analysed multi-annual period (1966-2005) was recorded with frequency from 10 to 15%, and south of that line – from 5 to 10%, except for the above-described regions, where frost occurred with different frequency. After 10th May frequency of frost occurrence was lower, as it oscillated between below 5 and above 10%, i.e. respectively every 20 and 10 years (fig. 8b). After 10th May, like after 30th April, frost most frequently occurred in the north-east, also in the south-west and south-east and locally in the vicinity of Lębork and Resko; least frequently – at the Szczecin Lagoon, the Bay of Gdańsk, the vicinity of Ustka, also in the region between Zielona Góra and Legnica and in the Małopolska Upland (excluding the Świętokrzyskie Mountains), the Silesian Upland, the Wielkopolska Lowland, the Sandomierz Basin, the Opole Plain and the south-western part of the Mazovian Lowland.

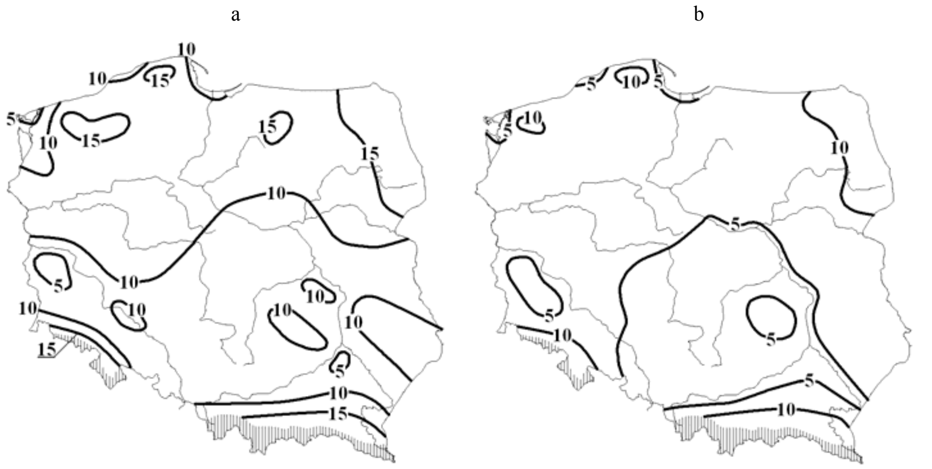


Fig. 8. Spatial distribution of occurrence frequency (%) of the dates of spring ground frost in Poland after 30th April (a) and after 10th May (b), 1966–2005

Ryc. 8. Przestrzenny rozkład częstości (%) występowania dat wiosennych przymrozków przygruntowych w Polsce po 30 kwietnia (a) i po 10 maja (b). Lata 1966–2005

Fig. 9. Spatial distribution of occurrence frequency (%) of the dates of autumn ground frost in Poland before 30th September, 1966–2005

Ryc. 9. Przestrzenny rozkład częstości (%) występowania dat jesiennych przymrozków przygruntowych w Polsce przed 30 września. Lata 1966–2005

On the other hand, in autumn before 30th September, frequency of the occurrence of first frost in Poland oscillated from below 5 to above 15% (fig. 9). Most frequently, every 6–7 years, this phenomenon was recorded in the Podlasie Lowland and least frequently, every 20 years – in the Słowińskie Coastland, the Szczecin Lowland, in the vicinity of Zielona Góra, in the valley of the River San between Sandomierz and Przemyśl and in the Kalisz High Plain reaching the Częstochowa region. In the remaining area of the country, covering about 60% of Poland, frost occurred with frequency from 5 to 10%.

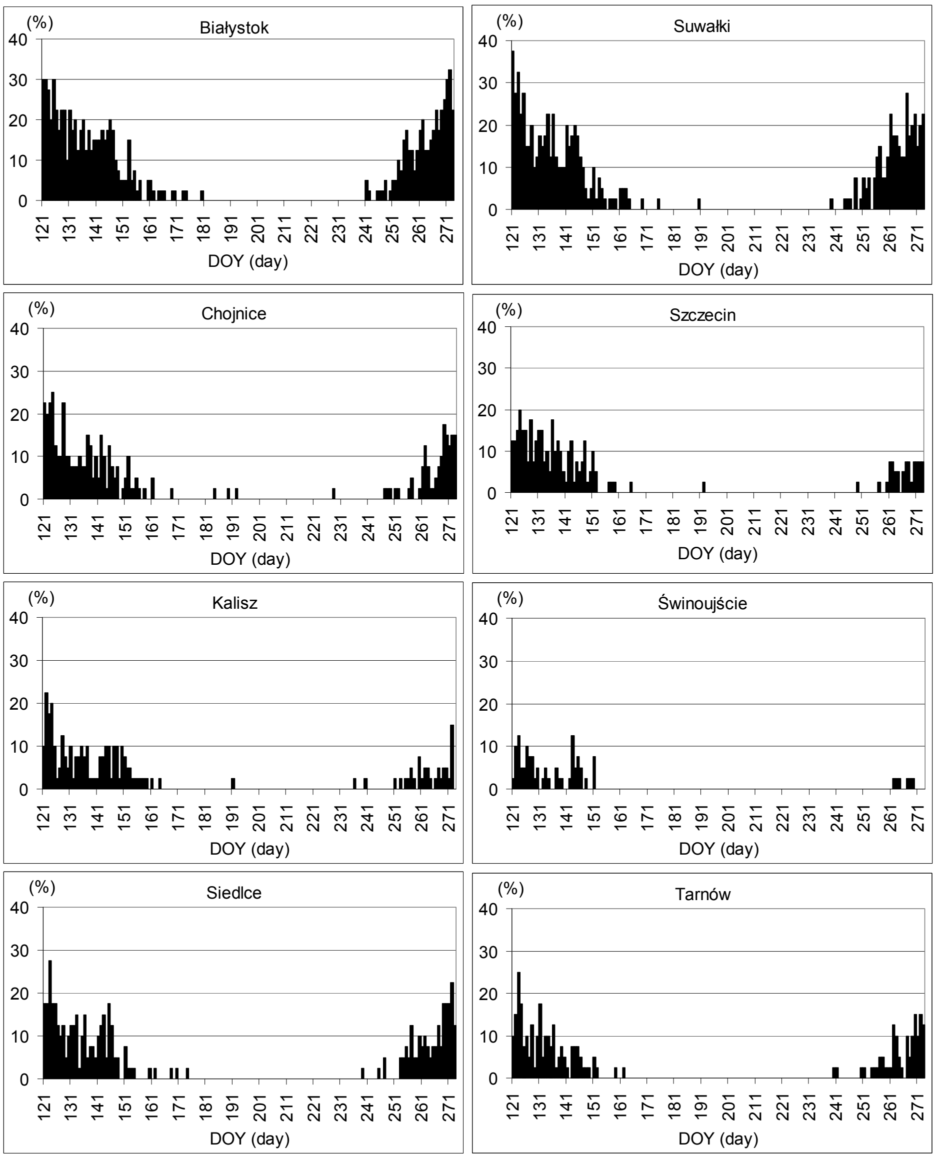


Fig. 10. Frequency of ground frost occurrence in selected stations in Poland in the cucumber growing season (from May to September), 1966–2005. DOY – day of the year

Ryc. 10. Częstość występowania przymrozków przygruntowych w wybranych stacjach meteorologicznych Polski, w okresie wegetacji ogórka (od maja do września). Lata 1966–2005. DOY – kolejny dzień roku

Table 1. Frequency of ground frost occurrence in selected air temperature ranges (°C) at the beginning (in May) and at the end (in September) of the cucumber growing season in Poland, 1966–2005

Tabela 1. Częstość występowania przymrozków przygruntowych w wybranych zakresach temperatury powietrza (°C) na początku (w maju) i na końcu (we wrześniu) okresu wegetacji ogórka w Polsce. Lata 1966–2005

No. Nr	Station Stacja	Month – Miesiąc							
		May – Maj				September – Wrzesień			
		[0;-2°C)	[-2;-4°C)	[-4;-6°C)	<-6°C	[0;-2°C)	[-2;-4°C)	[-4;-6°C)	<-6°C
1	Białystok	9.0	4.5	2.7	0.8	6.5	4.0	1.5	0.9
2	Chojnice	7.7	3.2	0.3	0.0	2.9	1.6	0.6	0.0
3	Częstochowa	4.4	3.3	0.3	0.0	0.8	0.3	0.1	0.0
4	Elbląg	8.0	3.8	1.7	0.5	4.0	0.5	0.6	0.0
5	Gdańsk	3.7	1.6	0.9	0.1	1.3	0.5	0.3	0.0
6	Gorzów Wlkp.	4.9	1.5	0.3	0.2	1.9	0.3	0.0	0.0
7	Kalisz	5.5	1.9	0.6	0.1	1.8	0.4	0.3	0.1
8	Katowice	4.4	2.3	0.5	0.0	3.2	0.5	0.2	0.0
9	Kętrzyn	6.5	3.7	1.1	0.1	3.3	1.0	0.3	0.0
10	Kielce	6.0	3.5	0.9	0.2	4.8	1.3	0.5	0.0
11	Kłodzko	9.0	4.8	1.0	0.0	4.8	1.8	0.3	0.1
12	Koło	5.2	2.3	0.6	0.0	2.1	0.2	0.1	0.0
13	Koszalin	8.6	4.2	1.2	0.1	1.8	0.4	0.0	0.0
14	Kraków	4.4	2.3	0.9	0.0	2.3	0.9	0.1	0.2
15	Legnica	6.0	1.5	0.6	0.0	3.2	1.3	0.3	0.1
16	Leszno	9.1	3.9	1.2	0.2	4.7	1.5	0.4	0.0
17	Lębork	8.6	5.6	1.7	0.4	3.6	1.6	0.5	0.0
18	Lublin	5.7	3.1	0.7	0.3	5.1	1.8	0.8	0.1
19	Łódź	5.7	2.9	1.3	0.3	5.8	1.8	0.8	0.1
20	Mława	5.1	3.9	1.4	0.3	4.3	1.5	0.2	0.2
21	Nowy sącz	4.7	3.7	0.9	0.4	3.1	1.2	0.3	0.1
22	Olsztyn	6.7	5.7	1.9	1.0	5.1	2.2	0.7	0.8
23	Opole	4.6	1.5	0.7	0.1	2.7	0.8	0.3	0.0
24	Ostrołęka	7.1	3.1	1.2	0.4	5.4	2.0	0.8	0.0
25	Piła	7.3	4.0	1.7	0.2	6.0	3.3	0.5	0.2
26	Płock	5.2	2.0	0.8	0.2	2.7	0.9	0.3	0.0
27	Poznań	7.1	2.6	0.9	0.1	3.9	0.9	0.4	0.0
28	Przemyśl	2.9	0.9	0.6	0.0	1.3	0.3	0.2	0.0
29	Puławy	4.9	1.8	0.6	0.1	3.3	1.3	0.5	0.0
30	Racibórz	4.6	1.9	0.6	0.0	4.0	1.1	0.3	0.0
31	Radom	7.4	2.7	1.1	0.3	4.3	1.8	0.4	0.2
32	Resko	9.2	5.1	1.3	0.3	3.2	1.4	0.4	0.2
33	Rzeszów	6.9	4.2	1.6	0.9	4.4	1.5	0.3	0.2
34	Sandomierz	3.2	1.7	0.1	0.0	1.6	0.5	0.2	0.0
35	Siedlce	6.9	2.4	1.1	0.2	4.1	2.5	0.6	0.0
36	Słubice	8.2	2.2	0.4	0.2	3.8	2.3	0.0	0.0
37	Suwałki	8.9	5.0	2.0	0.4	5.9	3.4	1.7	0.3
38	Szczecin	7.3	2.1	0.9	0.1	1.6	1.3	0.0	0.0
39	Szczecinek	8.4	5.7	1.5	0.4	2.6	2.3	0.7	0.3
40	Świnoujście	3.6	0.6	0.4	0.0	0.5	0.0	0.0	0.0
41	Tarnów	3.8	2.6	1.1	0.1	3.3	1.1	0.2	0.0
42	Terespol	6.7	3.3	1.6	0.2	4.2	3.1	1.3	0.2
43	Toruń	7.1	4.5	2.0	0.2	3.9	2.0	0.8	0.4
44	Ustka	4.6	1.5	0.5	0.2	0.3	0.2	0.0	0.0
45	Warszawa	5.1	2.3	0.6	0.2	3.3	0.8	0.2	0.0
46	Wieluń	5.1	2.0	0.2	0.0	2.5	0.6	0.1	0.0
47	Włodawa	4.9	3.1	1.1	0.2	3.6	1.9	0.9	0.1
48	Wrocław	8.8	2.7	0.8	0.1	3.8	0.9	0.3	0.0
49	Zamość	6.0	3.3	1.7	0.3	4.8	2.1	0.8	0.1
50	Zgorzelec	8.3	3.5	0.9	0.0	3.0	1.3	0.3	0.0
51	Zielona Góra	3.0	0.4	0.1	0.0	0.6	0.0	0.0	0.0

Frequency of frost occurrence in the cucumber growing season (from May to September), shown for some meteorological stations representing different climatic regions of Poland in the analysed multi-annual period 1966–2005, was highly diverse, as it oscillated in May from 0 to 13% in Świnoujście and from 3 to 38% in Suwałki, and in September from 0 to 3% in Świnoujście and from 0 to 23% in Siedlce (fig. 10). On particular days of the period from June to August ground frost occurred very seldom, maximally with frequency of: 15% in Białystok, 10% in Chojnice, 8% in Suwałki, 5% in Szczecin and Kalisz, 3% in Siedlce and Tarnów and 0% in Świnoujście.

Most often intensity of ground frost in Poland, both in May and September, was mild and then, moderate, severe and very severe; for the whole country, on average, it amounted to, respectively: about 6.2, 3.1 1.1 and 0.2% in May and 3.4, 1.3, 0.4 and 0.1% in September (tab. 1). In May, out of the 51 considered meteorological stations at four stations mild frost was recorded with frequency ≥9%, at 15 stations – with frequency of 7–8.9%, at 16 stations – with frequency of 5–6.9%, at 15 stations – with frequency of 3–4.9% and at 1 station – slightly below 3%. In September mild frost was recorded with frequency from 0.3% in Ustka to 6.5% in Białystok, but at 18 stations with frequency of below 3%, at 26 stations with frequency of 3–4.9% and at 7 stations with frequency of above 5%. Frost of moderate intensity occurred maximally with frequency of about 6 and 4% respectively in May and September, of severe intensity – about 3 and 2%, and of very severe intensity – about 1% in each month.

Effect of frost and minimum air temperature at the ground level on growth, development and yield of cucumber

In the years 1966–2005, significant influence of frost described by the number of days with air temperature ≤0° (Tfd) and significant influence of minimum air temperature at the ground level (Tfmin) on the rate of cucumber growth and development (tables 2–5) were proved despite the fact that experiments conducted by COBORU were not directed at this phenomenon. Lower than average minimum air temperature at the ground level significantly delayed all the considered phenological phases and agrotechnical dates of cucumber and in the strongest way – the date of the end of harvesting and, next, the date of emergence and the beginning of harvesting (tab. 2). Delay of the date of the end of emergence and the end of harvesting was also confirmed by means of the second of the considered indexes describing unfavourable thermal conditions of air at the ground level; namely, the number of days with frost (tab. 3). Determination coefficient obtained for regression equations describing effect of frost by means of minimum air temperature on the analysed dates oscillated between 8.4% in the case of the date of the beginning of fruit-setting and 51.9% in the case of the date of the end of harvesting; on the other hand, when described by means of the number of days with frost – between 15.7% in the case of the date of the end of emergence and 35.6% in the case of the date of the end of harvesting. Relationship between the date of the end of harvesting and the two analysed indexes describing unfavourable thermal conditions of air at the ground level in Poland and relationship between the date of the beginning of flowering and Tfmin were determined with the use of the 2^{nd} degree polynomial and the remaining relationships by means of the linear function.

Table 2. Linear or curvilinear relationship between the date of a phenophase and an agrotechnical[a] date of cucumber for whole Poland and minimum air temperature at the ground level in the preceding development stage, considering the linear trend in the years 1966–2005
Tabela 2. Zależność liniowa lub krzywoliniowa między terminem fazy fenologicznej i agrotechnicznym[a] ogórka w skali całej Polski a minimalną temperaturą powietrza przy gruncie w poprzedzającym okresie rozwojowym, z uwzględnieniem trendu liniowego w latach 1966–2005

Term Termin	Regression equation – Równanie regresji				Range Tfmin Zakres Tfmin	R^2
	intercept wyraz wolny	regression coefficient współczynnik regresji				
		aR	bTfmin	$bTfmin^2$		
Ee	513.15	-0.18***	-0.69**		-8.1; 7.2	13.4
Bf	541.35	-0.17***	-0.49**	-0.053*	-6.3; 7.8	9.6
Bfs	627.0061	-0.21***	-0.38**		-1.1; 13.1	8.4
Bh[a]	831.59	-0.31***	-0.506***		-0.2; 14.2	18.6
Eh[a]	962.42	-0.35***	-2.54***	-0.11***	-7.9; 9.0	51.9

R^2 – determination coefficient (%), Tfmin – minimum air temperature at the ground level, R – linear trend of the yield, i.e., the successive years of the 1966–2005 multiannual period, a, b – regression coefficients, *** significant at P ≤ 0.01, ** significant at P ≤ 0.05, * significant at P ≤ 0.1, Ee – end of emergence, Bf – beginning of flowering, Bfs – beginning of fruit-setting, Bh – beginning of harvesting, Eh – end of harvesting.
R^2 – współczynnik determinacji (%), Tfmin – minimalna temperatura powietrza przy gruncie (°C), R – trend liniowy, czyli kolejne lata wielolecia 1966–2005, a, b – współczynniki regresji, *** – istotne przy P ≤ 0,01, ** – istotne przy P ≤ 0,05, * – istotne przy P ≤ 0,1, Ee – koniec wschodów, Bf – początek kwitnienia, Bfs – początek zawiązywania owoców, Bh – początek zbioru, Eh – koniec zbioru.

Table 3. Linear or curvilinear relationship between the date of a phenophase and an agrotechnical[a] date of cucumber for whole Poland and the number of days with ground frost in the preceding development stage, considering the linear trend in the years 1966–2005
Tabela 3. Zależność liniowa lub krzywoliniowa między terminem fazy fenologicznej i agrotechnicznym[a] ogórka w skali całej Polski a liczbą dni z przymrozkiem przygruntowym w poprzedzającym okresie rozwojowym, z uwzględnieniem trendu liniowego w latach 1966–2005

Term Termin	Regression equation – Równanie regresji				Range Tfd Zakres Tfd	R^2
	intercept wyraz wolny	regression coefficient współczynnik regresji				
		aR	bTfd	$bTfd^2$		
Ee	532.95	-0.19***	1.0707***		0; 14	15.7
Bf					0; 4	n.s.
Bfs					0; 4	n.s.
Bh[a]					0; 2	n.s.
Eh[a]	1392.11	-0.57***	6.4001***	-0.27**	0; 13	35.6

Tfd – the number of days with ground frost (day), n.s. – non-significant at P ≤ 0.1. Other explanations see table 2.
Tfd – liczba dni z przymrozkiem przygruntowym (dzień), n.s. – nieistotny na poziomie P ≤ 0,1. Pozostałe objaśnienia patrz tabela 2.

It was also proved that there is significant relationship between duration of all the analysed development stages of cucumber and minimum air temperature and also between duration of the period from sowing to the end of emergence (S-Ee), the period from the beginning of harvesting to the end of harvesting (Bh-Eh) and the number of days with frost (tables 4 and 5). Out of the 5 analysed cucumber development stages the largest significant lengthening pertained to 2 development stages, S-Ee and Bh-Eh (respectively at the beginning and at the end of the growing season of this plant), i.e. when ground frost was recorded in Poland most frequently. Determination coefficient describing these relationships was the highest for the period S-Ee in the case of using the independent variable Tfd (R^2 = 26.7%), and next for the period Bh-Eh in the case of using the independent variable Tfmin (R^2 = 24.7%). All regression equations, apart from the variables Tfmin and Tfd, characterising minimum air temperature at the ground level, also considered the linear trend of duration of cucumber development stages, like in equations describing variability of the dates of phenophases and harvesting (tables 2 and 3).

Table 4. Linear or curvilinear relationship between duration of a cucumber development stage for whole Poland and minimum air temperature at the ground level, considering the linear trend in the years 1966–2005

Tabela 4. Zależność liniowa lub krzywoliniowa między długością okresu rozwojowego ogórka w skali całej Polski a minimalną temperaturą powietrza przy gruncie, z uwzględnieniem trendu liniowego w latach 1966–2005

Stage Okres	Regression equation – Równanie regresji				Range Tfmin Zakres Tfmin	R^2
	intercept wyraz wolny	regression coefficient współczynnik regresji				
		aR	bTfmin	bTfmin^2		
S-Ee	453.12	-0.21***	-0.72***	-0.0804**	-8.1; 7.2	23.2
Ee-Bf	102.35	-0.034*	-0.49***		-6.3; 7.8	8.0
Bf-Bfs	50.89	-0.022***	-0.19***		-1.1; 13.1	12.8
Bfs-Bh	202.042	-0.094***	-0.79***		-0.2; 14.2	18.9
Bh-Eh	390.016	-0.17***	-1.31***	-0.091**	-7.9; 9.0	23.7

S – sowing. Other explanations see table 2.
S – siew. Pozostałe objaśnienia patrz tabela 2.

Table 5. Linear relationship between duration of a cucumber development stage for whole Poland and the number of days with ground frost, considering the linear trend in the years 1966–2005

Tabela 5. Zależność liniowa między długością okresu rozwojowego ogórka w skali całej Polski a liczbą dni z przymrozkiem przygruntowym, z uwzględnieniem trendu liniowego w latach 1966–2005

Stage Okres	Regression equation – Równanie regresji			Range Tfd Zakres Tfd	R^2
	intercept wyraz wolny	regression coefficient współczynnik regresji			
		aR	bTfd		
S-Ee	460.62	-0.22***	1.13***	0; 14	26.7
Ee-Bf				0; 4	n.s.
Bf-Bfs				0; 4	n.s.
Bfs-Bh				0; 2	n.s.
Bh-Eh	628.804	-0.29***	2.77***	0; 13	16.9

Other explanations see tables 2 and 3.
Objaśnienia patrz tabele 2 i 3.

Table 6. Effect of minimum air temperature at the ground level and the number of days with frost on cucumber yield in Poland, considering the linear trend in the years 1966–2005
Tabela 6. Wpływ minimalnej temperatury powietrza przy gruncie i liczby dni z przymrozkiem na plon ogórka w Polsce, z uwzględnieniem trendu liniowego w latach 1966–2005

Kind of yield Rodzaj plonu	Characteristics Charakterystyki	Stage Okres	Regression equation – Równanie regresji				R^2
			intercept wyraz wolny	regression coefficient współczynnik regresji			
				aR	b	b^2	
T	Tfmin	S-Ee	-737.14	0.38***	-0.0701*	-0.097*	15.6
	Tfd	S-Ee	-754.99	0.39***	1.025*	-0.11*	13.5
	Tfmin	Bh-Eh	-750.0011	0.39***	-0.18*	-0.055*	14.3
	Tfd	Bh-Eh	-752.049	0.40***	0.26*	-0.051*	13.1
M	Tfmin	S-Ee	-862.105	0.44***	-0.33*	-0.100001*	25.8
	Tfd	S-Ee	-887.15	0.46***	1.92***	-0.21***	26.6
	Tfmin	Bh-Eh	-977.93	0.503***	-0.38*	-0.027*	24.9
	Tfd	Bh-Eh	-896.31	0.46***	0.72*	-0.053*	23.9

T – total yield ($t \cdot ha^{-1}$), M – marketable yield ($t \cdot ha^{-1}$). Other explanations see tables 2 and 3.
T – plon ogólny ($t \cdot ha^{-1}$), M – plon handlowy ($t \cdot ha^{-1}$). Pozostałe objaśnienia patrz tabele 2 i 3.

Lower than average minimum air temperature at the ground level not only delayed particular phenological phases and dates of harvesting and lengthened cucumber development stages but also negatively affected the quantity of final total and marketable yield of the plant (tab. 6). The quantity of the total yield of cucumber was significantly negatively determined by unfavourable thermal conditions of air at the ground level occurring not only in spring but also in autumn and its variability amounted to from 13.1 to 15.6%; for the marketable yield – from 23.9 to 26.6%. The closest relationship was proved for the marketable yield of cucumber and the number of days with frost in the period from sowing to the end of emergence (R^2 = 26.6%), and the weakest relationship – for the total yield and the number of days with frost in the period from the beginning of harvesting to the end of harvesting (R^2 = 13.1%). In all constructed regression equations not only a variable describing the distribution of Tfmin and Tfd was an independent variable but also a variable describing a positive linear trend of cucumber yield in the years 1966–2005 (aR).

DISCUSSION

In Poland, spatial and temporal distribution of frost mainly depends on vertical topography, its cover and a type of substrate, hydrographical network and, next, on the continentality factor [Koźmiński and Trzeciak 1971]. Regions of Poland where high frequency of frost occurrence in the growing season (from April to October) is noted are marked by its high intensity and a shorter period without frost [Koźmiński and Trzeciak 1971, Koźmiński and Michalska 2001]. Unfavourable phenomena for agriculture will probably be marked by increasingly high variability and not by their increased frequency [Bokwa and Matuszyk 2005]. Because of that a necessity of further development and improvement of systems of forecasting and early warning against unfavourable phenomena, including frost, acquires much significance [Díaz and Martínez 1993, Yang and Goodings 1998, Madelin and Beltrando 2005, Han and Goodings 2006, Prabha and Hoogenboom 2008, Castellanos et al. 2009, Maqbool et al. 2009]. In Poland in spring, and especially in May, the bigger the absolute number of days with frost in a given area is and the more frost of low sub-zero temperatures occurs, the higher risk caused by frost in vegetable growing [Koźmiński and Weber 1969]. It results from the research by Koźmiński and Trzeciak [1971] based on the multi-annual period 1951–1970 that last spring frost, in most regions of Poland occurs on average from 26th April to 5th May. Earlier, before 25th April, frost subsides in the region of the Szczecin Lagoon and the Bay of Gdańsk, along the river Oder (within the stretch from Opole to the Nysa Łużycka river mouth), in the Radom Plain and in the vicinity of Puławy, Terespol, Chełm and Wieliczka. Relatively late, until 15th May, last spring frost subsides in the Pomeranian Lakeland, in the regions of Olsztyn and Szczytno, Bydgoszcz and Toruń; on the other hand, in the Carpathians and the Sudeten spring frost may occur after 25th May and in the highest parts of the mountains as late as in June. Slightly different spatial distribution is presented in the current work on the basis of the 40-year research period 1966–2005, according to which earliest frost subsides before 10th May, i.e. on average 15 days later than in the years 1951–1970, latest – after 25th May, i.e. the same as according to Koźmiński and Trzeciak [1971]. On the other hand, first autumn frost in most regions of Poland, except for the Carpathians, the Sudeten and Roztocze, occurs on average in the second decade of October, but it may also occur in September [Koźmiński and Trzeciak 1971, Koźmiński and Michalska 2001, Dragańska et al. 2004, Wilczyński et al. 2005], i.e. similar to the years 1966–2005.

From the perspective of cucumber field cultivation, duration of the period without frost in Poland, included between average dates of last spring and first autumn frost, which in two thirds of Poland oscillates most often from 160 to 180 days, is also of big importance [Koźmiński and Trzeciak 1971]. The shortest period without frost, amounting to 150 days, occurs in river valleys, land depressions and in the mountains. On the other hand, analysing the period without frost on the basis of the dates of the latest spring frost and the earliest autumn frost, it can be noticed that it becomes shortened, in comparison with the period determined on the basis of average dates, to 130 days in most regions of the country and even to 120 days – on the elevations of the Pomeranian Lakeland, in the River Biebrza valley, in the Białowieża region and in the Sudeten and the Carpathians [Koźmiński et al. 1990]. The period without frost in the years 1966–2005 is characterised by slightly different spatial distribution because the shortest period, lasting below 120 days, encompassed not only submountainous regions but also north-eastern Poland and the Lublin Upland. On the other hand, in the Pomeranian Lakeland, where according to Koźmiński and Trzeciak [1971] the period without frost lasts slightly below 120 days, at present it is, on average, by 10 days longer. The longest period without frost, lasting above 150 days, occurs only in the region of the Szczecin Lagoon and the Bay of Gdańsk and lasting above 140 days – in the Radom Plain, the Sandomierz Basin, the Szczecin Lowland and the Zielona Góra Hills. However, it results from the research by Sokołowska [1980] that the growing season of cucumber cultivated from sowing oscillates in Poland, on average, from 110 to 150 days, and the longest period occurs in the Radom Plain, the Sandomierz Basin and in the Częstochowa region, i.e. in the regions where last spring frost subsides earlier in comparison with other regions and first autumn frost appears relatively late.

Not only the dates of ground frost but also its intensity determines cucumber risk at the time of its occurrence. A drop of minimum temperature below a specified threshold as well as the number of days with frost depend on the region of Poland. It results from the research by Dragańska et al. [2004] that the most frequent intensity type of frost is mild frost, i.e. from 0 to -2°C both in spring and in autumn. Similar results were obtained on the basis of data coming from the multi-annual period 1966–2005; in May mild frost occurs on average twice as often as in September. Information on the occurrence of sequences of frost days is also of very high importance. According to Dragańska et al. [2004] bigger damage may be done by milder frost which lasts several days in a row than severe frost but lasting one day. In north-eastern Poland single frost days occur most frequently and frost lasting two days is the second most common. The lowest number of frost sequences occur in June and September and these months are marked by single days with frost. On the other hand, it results from the research by Koźmiński [1976] that in most regions of the country, especially in its western and central parts, potential risk for thermophilous agricultural plants caused by a sequence of frost days lasting ≥2 days in the period from 11th May to 30th June is low and locally very slight. Most frequently frost sequences lasting ≥2 days are recorded in April – on average about 60%, in October – about 30%, and next in May – about 7% and in September about 3% of the total number of sequences in the growing season (from May to October).

Cucumber, as a subtropical plant is very sensitive to ground frost and, therefore, it should be sown and harvested in such a period when this risk has disappeared or before it occurs. That is why, cucumber seeds should be sown between 10th and 20th May, and locally even after 25th May [Sokołowska 1980, Górka 1987, Kalbarczyk 2006]. On the other hand, it should be harvested, on average, until 10–20th September, when risk of frost occurrence at the end of the growing season of cucumber is still very low [Kalbarczyk 2006, Kalbarczyk 2009a, 2009b]. Similar dates of sowing and harvesting of the described plant are used in other countries of Central Europe [Bittsánszky et al. 1990]. Ignoring the dates of sowing causes that cucumber seeds often emerge longer and very unevenly, especially when it takes place in a period with cold days causing shifts of successive development stages in time and, as a result, also of the dates of harvesting or that the plants do not emerge at all or die, irrespective of a cultivar, in extremely unfavourable thermal conditions [Górka 1987, Babik 2004]. Similar results are obtained in the present work, in which negative influence of lower than average minimum air temperature at the ground level on all the analysed phenological dates and the dates of harvesting was proved. It results from the research by Górka [1987] that in Poland cucumber emerges depending on average air temperature, quickest after 5 days at the temperature of 19°C, latest after 20 days – at 11°C. Damage of cucumber plants caused by low air temperature may occur not only at the beginning and the end of the growing season of the described plant but also in the period of flowering and even during fruit-setting when after a period of high temperatures there occurs cooling to 4–6°C of several days. A few days of cool air and low temperature in the root zone cause dying of the plants because water uptake from soil is stopped and transpiration continues [Babik 2004].

Some scientific results suggest that soil warming partly prevents unfavourable influence of low air temperature at night on the growth of thermophilous plants [Ingratta 1980, Liebig 1985]. In conditions when soil is warmed to 14°C, cucumber without any bigger damage may survive even a longer period at air temperature amounting to only 10°C [Liebig 1985].

RECAPITULATION

In Poland, in the years 1966–2005, spring and autumn ground frost is marked by high variability, both spatial and temporal. In the whole country, on average, frost subsides earliest, before 10th May, at the Bay of Gdańsk and in the Świnoujście region, and latest, after 25th May – in north-eastern, south-western and south-eastern Poland and also in the Pomeranian Lakeland and, on average, first autumn frost appears earliest, before 15th September, in the Podlasie Lowland and latest, after 10th October, in the Słowińskie Coastland and at the Bay of Gdańsk. In the years 1966–2005, at 12 meteorological stations out of the 51 considered stations, significant changes concerning duration of the period without frost were noted: its lengthening in northern Poland and in the vicinity of Zielona Góra, Kalisz and Kraków – on average from 4 to 13 days/10 years, shortening in the north-eastern part of Poland and in the vicinity of Opole – on average from 6 to 10 days/10 years. The highest risk of ground frost occurrence in spring after 10th May takes place in the north-east and in the submountainous regions situated in the south-western and south-eastern parts of Poland and locally in the north (every 10 years), and in autumn before 30th September in the south-west and south-east (every 10 years), and especially in the Podlasie Lowland (every 6–7 years).

Frost and minimum air temperature at the ground level significantly determine the rate of growth and development of cucumber and also its final yield – total and marketable. Minimum air temperature at the ground level lower than the multi-annual average causes delay of all the analysed dates of phenological phases and harvesting (the longest delay concerns the date of the end of harvesting and, next, the end of emergence), lengthening of all development stages (the largest lengthening concerns the period from the beginning of harvesting to the end of harvesting and, next, the period from sowing to the end of emergence) and, as a result, reduction in cucumber yield (higher reduction concerns the marketable yield than the total yield).

Ground frost poses high potential risk for field cultivation of cucumber in Poland not only because of the fact that it significantly determines the rate of growth, development and quantity of the plant yield but also because of its high spatial and temporal variability and the highest cultivation risk occurs in north-eastern Poland where significant shortening, year by year, of the period without frost was proved and where the highest frost frequency both at the beginning and at the end of the cucumber growing season was recorded.

REFERENCES

Akinci S., Abak K., 1999. Determination of a suitable formula for the calculation of sum growing degree days in cucumber. Acta Hort. (ISHS), 492, 273–280.
Babik I., 2004. Ekologiczne metody uprawy ogórka. Congress Center of Ecological Agriculture.
Bittsánszky J., Hamar N., Milotay P., Kristóf E., 1990. 100 day harvest period in pickling cucumber production in Hungary. Acta Hort. (ISHS), 267, 145–150.
Bokwa A., Matuszyk K., 2005. Występowanie zjawisk atmosferycznych niekorzystnych dla rolnictwa na Pogórzu Wielickim. Woda Środ. Obsz. Wiej., 5(14), 57–68.
Brázdil R., Budíková M., Faško P., Lapin M., 1995. Fluctuation of maximum and minimum air temperatures in the Czech and the Slovak Republics. Atmos. Res., 37, 53–65.
Castellanos M.T., Tarquis A.M. Morató M.C., Saa A., 2009. Forecast of frost days based on monthly temperatures. Span. J. Agric. Res., 7(3), 513–524.
Cittadini E.D., De Ridder N., Peri P.L., Van Keulen H., 2006. A method for assessing frost damage risk in sweet cherry orchards of South Patagonia. Agri. For. Meteorol., 141, 235–243.
Díaz D.P., Martínez A.T., 1993. On simulation of air temperature curve near the ground in presence of frosts in Valley of Perote (Mexico). Int. J. Biometeorol., 37, 101–103.
Dobosz M., 2001. Wspomagana komputerowo statystyczna analiza wyników badań. Wyd. EXIT. Warszawa.
Dragańska E., Rynkiewicz I., Panfil M., 2004. Częstotliwość i intensywność występowania przymrozków w Polsce północno-wschodniej w latach 1971–2000. Acta Agrophysica, 3(1), 35–41.
Eccel E., Rea R., Caffarra A., Crisci A., 2009. Risk of spring frost to apple production under future climate scenarios: the role of phenological acclimation. Int. J. Biometeorol., 53, 273–286.
Feliksik E., Wilczyński S., 2009. The effect of climate on tree-ring chronologies of native and nonnative tree species growing under homogenous site conditions. Geochronometria, 33, 49–57.
Fletcher A.L., Moot D.J., 2006. Phenological development and frost risk of 'challenger' sweet corn (*Zea mays*) in response to phosphorus. New Zeal. J. Crop Hort. Sci., 34 (4), 393–402.
Gołaszewski D., 2004. Stratyfikacja termiczna w przygruntowej warstwie powietrza w wiosenne noce przymrozkowe na stacji SGGW Ursynów. Acta Agrophysica, 3, 247–255.
Górka W., 1987. Bonitacja warunków agroklimatycznych Polski dla wybranych warzyw. Sprawozdanie etapowe CPBR nr 10.18. Wyd. AR Szczecin.
Grabowski J., Kawecki Z., Tomaszewska Z., 2007. Meteorological conditions of the blooming of nanking cherry (*Prunus tomentosa* Thunb.) and their impact on the yield. Fol. Hort., 19, 45–52.
Han S.J., Goodings D.J., 2006. Practical model of frost heave in clay. J. Geotech. Geoenviron. Eng., 132(1), 92–101.
Ingratta F., 1980. Reducing night temperature by soil warming. Greenhouse Veg. News. Ontario Ministry of Agriculture and Food.
Kalbarczyk R., 2006. Time and spatial distribution of agrotechnical dates and phenological stages of cucumber in western Poland. Acta Sci. Pol., Hortorum Cultus, 5 (2), 51–68.
Kalbarczyk R., 2009a. Air temperature changes and phenological phases of field cucumber (*Cucumis sativus* L.) in Poland, 1966–2005. Hort. Sci., 36(2), 75–83.
Kalbarczyk R., 2009b. Use of Cluster analysis in the determination of the influence of agrotechnical dates and phenological phases on field Cucumber (*Cucumis sativus* L.). Acta Sci. Pol., Hortorum Cultus, 8(1), 63–75.
Kołodziej J., Liniewicz K., Bednarek H., 2004. Temperatura powietrza w dniach „zimnych świętych" w okolicy Lublina. Annales UMCS, Sec. E., 59(2), 857–867.
Koźmiński Cz., 1976. Występowanie ciągów dni przymrozkowych w okresie wegetacyjnym na terenie Polski. Prz. Geogr., 48(1), 75–93.

Koźmiński Cz., Trzeciak S., 1971. Przestrzenny i czasowy rozkład przymrozków wiosenno--jesiennych na obszarze Polski. Prz. Geogr., 4, 523–549.
Koźmiński Cz., Weber M., 1969. Prawdopodobieństwo wystepowania przymrozków w Polsce na przykładzie wybranych stacji meteorologicznych. Biul. Warzywniczy, 9, 155–163.
Koźmiński Cz., Górski T., Michalska B. (eds), 1990. Atlas klimatyczny elementów i zjawisk szkodliwych dla rolnictwa. Wyd. IUNG Puławy, AR Szczecin.
Koźmiński Cz., Michalska B. (eds), 2001. Atlas klimatycznego ryzyka uprawy roślin w Polsce. Wyd. AR Szczecin.
Krug H., Thiel F., 1985. Effect of soil temperature on growth of cucumber in different air temperature and radiation regime – poster. Acta Hort. (ISHS), 156, 117–126.
Lederle E., Krug H., 1985. Model experiments for energy saving temperature control for germinating cucumbers. Acta Hort. (ISHS), 156, 105–116.
Liebig H.P., 1985. Model of cucumber growth and yield. I. Raising the crop under low temperature regimes. Acta Hort. (ISHS), 156, 127–138.
Lindkvist L., Lindqvist S., 1997. Spatial and temporal variability of nocturnal summer frost in elevated complex terrain. Agri. For. Meteorol., 87, 139–153.
Loginov V.F., Mikutskii V.S., Kuznetsov G.P., 2007. Statistical and probability analysis of frosts in Belarus. Russ. Meteorol. Hydrol., 32(10), 651–657.
Madelin M., Beltrando G., 2005. Spatial interpolation-based mapping of the spring frost hazard in the Champagne vineyards. Meteorol. Appl., 12, 51–56.
Maqbool A., Shafiq S., Lake L., 2009. Radiant frost tolerance in pulse crops – a review. Euphytica, 172, 1–12.
Marcelis L.F.M., Hofman-Eijer L.R.B., 1993. Effect of temperature on the growth of individual cucumber fruits. Physiol. Plantarum, 87(3), 321–328.
Medany M.A., Wadid M.M., Abou-Hadid A.F., 1999. Cucumber fruit growth rate in relation to climate. Acta Hort. (ISHS), 491, 107–112.
Peck L., 1996. Temporal and spatial fluctuations in ground cover surface temperature at a Northern New England site. Atmos. Res., 41(2), 131–160.
Prabha T., Hoogenboom G., 2008. Evaluation of the weather research and forecasting model for two frost events. Comput. Electron. Agri., 64, 234–247.
Sokołowska J., 1980. Pojawy fenologiczne świata roślinnego w Polsce. Wyd. IMGW, Warszawa.
Yang D., Goodings D.J., 1998. Predicting frost heave using FROST model with centrifuge models. J. Cold Regions Eng., 12(2), 64–83.
Yoshida S., Kitano M., Eguchi H., 1998. Growth of cucumber plants (*Cucumbis sativus* L.) under diurnal control of air temperature. Biotronics, 27, 97–102.
Wilczyński S., Durło G., Feliksik E., 2005. Przymrozki wczesne i późne na Kopciowej (Beskid Sądecki) w latach 1971–2000. Acta Agr. Silv., ser. Silv., 43, 65–76.

ZMIENNOŚĆ PRZESTRZENNA I CZASOWA WYSTĘPOWANIA PRZYMROZKÓW PRZYGRUNTOWYCH W POLSCE I ICH WPŁYW NA WZROST, ROZWÓJ I PLON OGÓRKA KONSERWOWEGO (*Cucumis sativus* L.), 1966–2005

Streszczenie. Dla świata roślin szczególnie niebezpiecznym zjawiskiem są przymrozki. Destrukcyjny wpływ przymrozków na rośliny ma charakter zarówno bezpośredni, jak i następczy. Rozmiar szkód wyrządzonych przez przymrozki zależy od ich intensywności, częstotliwości, pory ich występowania i od gatunku rośliny. Celem pracy było poznanie przestrzennego i czasowego rozkładu przymrozków przygruntowych w Polsce oraz określenie wpływu minimalnej temperatury powietrza przy gruncie na termin faz fenologicznych i zbioru oraz długość okresów rozwojowych, a także na wielkość plonu ogórka odmian konserwowych na przełomie XX i XXI w.. Materiał źródłowy wykorzystany w niniejszym opracowaniu zebrano z 28 stacji doświadczalnych COBORU i z 51 stacji meteorologicznych IMGW w latach 1966–2005. Przymrozki przygruntowe scharakteryzowano m.in. za pomocą przeciętnych dat ostatnich wiosennych i pierwszych jesiennych przymrozków, długości okresu bezprzymrozkowego, a także intensywności i częstości ich występowania oraz trendu liniowego. Wpływ minimalnej temperatury powietrza przy gruncie na wzrost, rozwój i plonowanie ogórka określono za pomocą liniowej i krzywoliniowej analizy regresji, natomiast trend liniowy pojawienia się ostatnich wiosennych i pierwszych jesiennych przymrozków oraz długości okresu bezprzymrozkowego – liniowej analizy regresji. Przymrozki przygruntowe stanowią duże potencjalne ryzyko polowej uprawy ogórka w Polsce nie tylko ze względu na to, że istotnie determinują przebieg wzrostu, rozwoju i wielkość plonu tej rośliny, ale również ze względu na ich dużą zmienność przestrzenną i czasową. Największe ryzyko uprawy ogórka występuje w Polsce północno-wschodniej, gdzie udowodniono istotne skracanie się z roku na rok okresu bezprzymrozkowego i gdzie notuje się największą częstość występowania przymrozków zarówno na początku, jak i na końcu okresu wegetacji ogórka.

Słowa kluczowe: ogórek, temperatura powietrza przy gruncie, trend czasowy, okres rozwojowy, analiza regresji

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