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ORIGINAL PAPER

Changes of temperature-related agroclimatic indices in Poland

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Abstract The agricultural sector in Poland is of considerable social and economic importance for the nation. Climate variability and change are of primary relevance to this largely climate-dependent sector. Changes in seven temperature-related agroclimatic indices (lengths of the growing season and of the frost-free season, days of occurrence of the last spring frost and of the first autumn frost; and annual sums of growing degree-days for three values of temperature threshold) in Poland in 1951–2010 are examined. As expected, they generally correspond to the overwhelming and ubiquitous warming. Many, but not all, detected trends are statistically significant. However, for some indices, strong natural variability overshadows eventual trends. Projections of temperature-related agroclimatic indices for the future, based on regional climate models, are also discussed.

1 Introduction

The agricultural sector in Poland is very important, socially and economically. The area of agricultural land in the country reaches approx. 187,000 km^2 (as compared to the total area of the country of 312,000 km^2). There are over 2.1 million people in Poland employed in agriculture, and this sector generates approx. 3 % of the GDP and over 9 % of the value of national export. Poland is predominantly a lowland country. Over three fourths of the country area is located at elevation below 200 m a.m.s.l.

The climate of Poland is moderate and ranges from maritime to continental. Over the country, humid Atlantic air from the west collides with dry continental air from the east. In addition to spring, summer, autumn, and winter, there are two transitional seasons—early spring (*przedwiośnie*) and early winter (*przedzimie*) with mean daily temperatures between 0 and 5 °C. Inter-annual variability of seasonal temperature is strong, particularly for winters, that can be warm—more oceanic or cold—more continental.

Since agriculture largely depends on climate, the climate change (both observed and projected) is of considerable interest and importance to the sector. In general, agriculture in Europe is temperature-limited in the north and water-limited in the south. Poland is located in the transition zone between these two conditions.

Climate change and overwhelming warming influence temperature-related agroclimatic indices. Climatic conditions related to temperature impact upon the size of harvest and the time of sewing, planting, and harvesting. Hence, improving the insight into changes of important temperature-related indices is of considerable societal and economic importance. The present paper starts by discussion of data and methods used, specification of seven indices of relevance, and information on the test. Next, results of change detection in three sets of indices, i.e., (i) lengths of the growing season and of the frost-free season, (ii) dates of occurrence of the last spring frost and of the first autumn frost, and (iii) annual sums of growing degree-days for three temperature threshold values are presented. Further, model-based projections for the future are reviewed.

Many results shown in the present paper draw from the doctoral thesis of Graczyk (2013), prepared under the supervision of the second author of this paper.

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2 Data and methods

The violent history of Poland in the 20th century, embracing armed conflicts, major changes of national boundaries including discontinuity of independent statehood, considerably limited the number and length of existing time series of meteorological data. Furthermore, such data are not readily available in open access. Nevertheless, the authors could access and compile time series of daily temperature (mean, maximum, and minimum values) for 22 meteorological stations in Poland. These stations read Bielsko-Biała, Chojnice, Hel, Jelenia Góra, Kalisz, Kasprowy Wierch, Katowice, Legnica, Lesko, Łódź, Poznań-Ławica, Rzeszów, Słubice, Suwałki, Szczecin, Śnieżka, Świnoujście, Toruń, Warszawa-Okęcie, Włodawa, Wrocław, Zakopane (Table 1, Fig. 1). The basic criteria of selection of stations were the length of the available time series of records, covering at least the interval 1951–2010 and spatial distribution of stations covering, in a reasonably uniform way, the whole territory of Poland, and reflecting the variability of its climates. In addition, Graczyk (2013) also examined several foreign stations, some of which, such as Görlitz and Potsdam (Germany); Oravska Lesna, Poprad, and Kosice (Slovakia); Lviv (Ukraine); Vilnius (Lithuania); and Kaliningrad (Russia), are not far from the territory of Poland.

Table 1 Listing of meteorological stations used in this work, their geographic coordinates and altitude

No.	Station name	Geographic coordinates		Altitude (m a.s.l.)	Mean annual temperature 2001–2010 (°C)
		Latitude (deg.)	Longitude (deg.)		
1	Bielsko-Biała	19.00	49.80	398	8.8
2	Chojnice	17.55	53.70	172	7.9
3	Hel	18.82	54.60	1	8.7
4	Jelenia Góra	15.80	50.90	342	7.8
5	Kalisz	18.08	51.73	140	9.1
6	Kasprowy Wierch	19.98	49.23	1991	0.0
7	Katowice	19.08	50.48	317	8.8
8	Legnica	16.17	51.22	122	9.5
9	Lesko	22.33	49.47	386	8.0
10	Łódź	19.40	51.73	187	8.6
11	Poznań-Ławica	16.83	52.42	86	9.2
12	Rzeszów	22.05	50.10	200	8.7
13	Słubice	14.60	52.35	21	9.4
14	Suwałki	22.95	54.13	184	7.1
15	Szczecin	14.62	53.40	1	9.4
16	Śnieżka	15.73	50.73	1603	1.3
17	Świnoujście	14.23	53.92	6	9.1
18	Toruń	18.58	53.05	69	8.7
19	Warszawa-Okęcie	20.98	52.15	106	8.8
20	Włodawa	23.55	51.55	175	8.2
21	Wrocław	16.88	51.10	120	9.4
22	Zakopane	19.95	49.30	857	6.0

Fig. 1 Map of locations of meteorological stations used in this work

The essential part of the records (daily data from 1951–2006) were received from Institute for Meteorology and Water Management (IMGW-PIB) in the framework of the project PBZ-KBN-086/P04/2003, "Extreme meteorological and hydrological events in Poland (assessment of events and forecasting of their impact on human environment)". More recent data were downloaded from archives of synoptic messages and Global Summary of the Day (GSOD) available on servers of NOAA, so that the complete set of data records used in this study spans the six-decade interval 1951–2010. The quality of information for 2007–2010 was validated by comparison of GSOD data for 2006 with observation records from IMGW-PIB, available for the same year. Archives of synoptic messages proved to be a satisfactorily accurate source of data (Graczyk 2013).

Excursions (level crossings) of temperature beyond some characteristic thresholds are particularly important for plant growth. The threshold of 5 °C of mean daily air temperature is being used in many methods of the thermal growing season calculation (e.g., Linderholm et al. 2008; Skaugen and Tveito 2004; Carter 1998). For cultivars that are sensitive to low temperatures, characteristics related to the minimum temperature threshold of 0 °C are important, while relevant sensitivity thresholds can be different for different plants. The rate of plant development and reaching particular development phases approximately depend on the sums of daily exceedance of some threshold temperature values, specific for each plant. This can be described via a growing degree-days (GDD) index (Górski and Jakubczak 1965). It is difficult to determine the physiological base temperature, and each growing phase may have a different base temperature (Yang et al. 1995). The base temperature can also vary depending on the used methodology. In this study, three base temperature thresholds were adopted. For determination of degree-days, mean daily air temperature was used here (alternatively, one may use the mean of daily maximum and minimum temperatures, e.g., Mc Master and Wilhelm 1997; Su et al. 2013).

Seven thermal indices, of importance to agriculture, were examined, namely

1. Duration of the growing season, calculated as the number of days between the last occurrence of at least 6-day interval with daily mean air temperature <5 °C before 1 July and the first occurrence of at least 6-day interval with daily mean air temperature <5 °C after 1 July, as in European Climate Assessment & Dataset (ECA&D), cf. Klein Tank et al. (2002).
2. Duration of the longest interval without frost, calculated as the longest continuous interval in a year with daily minimum air temperature >0 °C
3. Date of occurrence of the last spring frost, determined as the number of day in a year, when the daily minimum air temperature drops below 0 °C for the last time before 1 July
4. Date of occurrence of the first autumn frost, determined as the number of day in a year, when the daily minimum air temperature drops below 0 °C for the first time after 1 July

5–7. Growing degree-days (GDD), also called degree-days of vegetation), calculated as the sum of positive deviations of daily mean air temperature above the following threshold values: 10 °C (threshold value for plants with high thermal requirements), 8 °C (threshold value for plants with medium thermal requirements), and 5.5 °C (threshold value for some cereals).

Time series of annual values of the above indices were determined for each station. They were examined using the Hydrospect 2.0 software (Radziejewski and Kundzewicz 2004) developed for change detection in long time series by non-parametric Mann-Kendall test.

The following threshold values of the significance level were used in this paper:

(i) Statistically significant trend at the level of 0.05
(ii) Statistically significant trend at the level of 0.1
(iii) Weak, statistically insignificant, tendency (significance level between 0.1 and ≤0.25)
(iv) Lack of even a weak tendency (significance level >0.25)

3 Results of change detection

3.1 The length of growing season and the frost-free season

Lengths of the growing season and of the frost-free season were determined for all stations including the high-mountain stations, for which these indices took the lowest values (on average: 86 and 50 days in a year at Kasprowy Wierch and 105 and 81, at Śnieżka, respectively). Highest values of the length of frost-free season were observed at the coastal stations: Hel (192 days) and Świnoujście (200 days).

Detection of trends with the help of statistical tests in long time series of duration of the growing season and of the frost-free season showed existence of significant increasing trend on the significance level of 0.05 for both indices at 14 and 15 stations, respectively (Fig. 2). For no stations, a statistically significant decreasing trend was detected.

On top of the formal trend detection, it is worthwhile to interpret some properties of time series of indices (Table 2). Counting the numbers of stations in which the maximum value of the duration of the growing season and of the frost-free season occurred in particular 20-year periods (1951–1970, 1971–1990, and 1991–2010), one can state that in 1951–1970, maximum values of either of these two indices were observed at four stations only, in 1971–1990—at 10 stations,

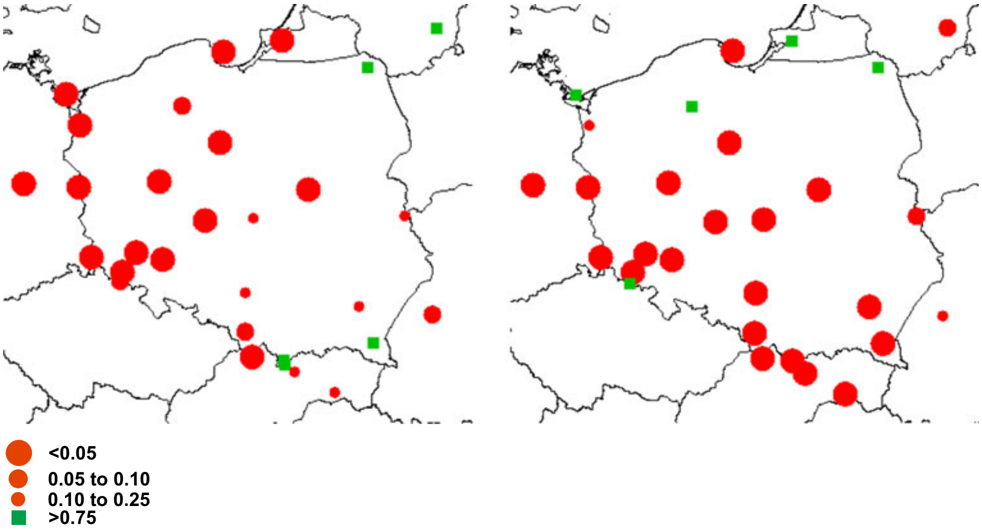

Fig. 2 Trend in duration of **a** the growing season and **b** the frost-free season, after Mann-Kendall test

Table 2 Maximum and minimum values of duration of the growing season and of the frost-free season length at particular stations. The Table shows the duration [number of days] and the year of occurrence

No.	Station name	Growing season length				Frost-free period length			
		Max		Min		Max		Min	
		Value	Year	Value	Year	Value	Year	Value	Year
1	Bielsko-Biała	313	2005	179	1994	235	2000	118	1973
2	Chojnice	279	2002	174	1992	202	1986	129	1951
3	Hel	313	2007	175	1976	253	2000	152	1976
4	Jelenia Góra	302	1988	165	1951	173	2002	93	1988
5	Kalisz	305	2007	181	1997	223	2000	141	1954
6	Kasprowy Wierch	153	1983	6	1984	93	1982	16	1978
7	Katowice	300	2007	188	1956	210	1961	117	1977
8	Legnica	310	2007	189	1956	212	1961	127	1953
9	Lesko	300	2007	180	1997	190	2001	107	1969
10	Łódź	303	1988	181	1997	221	2008	119	1957
11	Poznań-Ławica	310	2007	184	1955	222	2001	119	1957
12	Rzeszów	300	2007	185	1955	221	1989	107	1977
13	Słubice	316	2005	188	1951; 1956	202	2001	109	1977
14	Suwałki	255	2006	162	1981	189	1957	114	1982
15	Szczecin	316	2005	184	1955	212	1986	116	1952
16	Śnieżka	176	2007	25	1970	129	1988	39	1964
17	Świnoujście	316	2005	180	1956	276	2006	167	1971
18	Toruń	306	2007	165	1951	197	1989	113	1977
19	Warszawa-Okęcie	313	2005	180	1997	221	2008	134	1964
20	Włodawa	300	2007	180	1997	199	2008	115	1973
21	Wrocław	305	2007	185	1955	222	1961	114	1991
22	Zakopane	242	1973	152	1987	186	2006	90	1952

in 1991–2010—at 30 stations (at 18 stations for growing season length and at 12 stations for longest non-frost period). However, there was 1 year, 2007, when maxima of the growing season length occurred at a great number of stations (11). The occurrence of a single year with many record values of indices may confound a broader tendency.

The minimum values of the length of the growing season and of the frost-free season occurred in earlier decades more frequently than recently, but the change is weaker. The minima were observed in 1951–1970 at 21 stations, in 1971–1990 at 15 stations, in 1991–2010 at 8 stations (for the growing season length at 7 stations and for the frost-free season length at 1 station).

Examination of decadal changes shows that the longest vegetation season and the longest frost-free period have been observed in the 2000s (for 18 and 9 stations, respectively). For no station, the longest vegetation season was observed in the 1950s or the 1960s, but for four stations, the longest frost-free period was observed in 1950s or 1960s (therein at three stations in 1961). In 2000s, at no station minimum values of the length of growing season or of the frost-free season were observed. It is worth stating that the minimum vales of duration of the growing season and of the frost-free season for high-mountain values can be very low. For Kasprowy Wierch, there was actually no summer break in cold weather in 1984, when duration of growing season was only 6 days or in 1978, when duration of frost-free season was only 16 days. Nevertheless, the high-mountain stations of Kasprowy Wierch and Śnieżka were retained for completeness, even if no agriculture is possible then. Agriculture is abundant in the foothills of the mountains (Table 2).

3.2 Days of occurrence of last spring frost and first autumn frost

Days of occurrence of the last spring frost (the last day between 1 January and 30 June with minimum temperature <0 °C) and of the first autumn frost (the first day between 1 July and 31 December with minimum temperature <0 °C) were determined for 20 of 22 stations, except for two stations in high mountains, where no definite summer break in frost days could be noted (see 3.1). Spring frost days may last longest in piedmont stations: Jelenia Góra (on average up to the 135th day of the year, i.e., 15 May) and Zakopane (up to the 130th day of the year, i.e., 10 May). Spring frost days end earliest in the sea coast station Świnoujście (on average up to the 107th day of the year, i.e., 17 April). Autumn frost days start earliest, in September, in

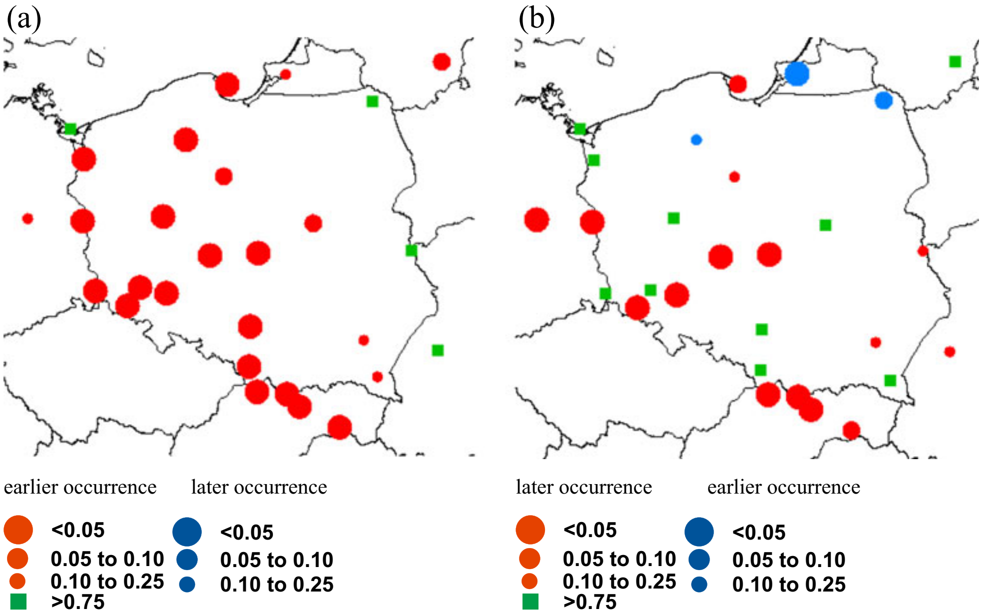

Fig. 3 Trend in changes in days of occurrence of **a** the last spring frost and **b** the first autumn frost, after Mann-Kendall test

piedmont stations: Jelenia Góra on the 270th day and Zakopane on the 271st day of the year. Autumn frost days start latest, in November, in the sea coast stations Hel and Świnoujście (on average the 314th and the 311st day, respectively).

With the help of statistical tests in long-term time series of the day of the last spring frost and of the first autumn frost in Poland (Fig. 3), trends were detected on the significance level of 0.05 at 13 (advance of the last spring frost) and 6 stations (delay of the first autumn frost), respectively. At further 2 and 2 stations, respectively, tests indicated similar trends on the significance level from the interval 0.05–0.1. For the station Suwałki, a statistically significant decreasing trend (0.1) in the

Table 3 The latest last spring frost day and the earliest first autumn frost day

No.	Station name	The last spring frost day				The first autumn frost day			
		The latest		The earliest		The earliest		The latest	
		Value	Year	Value	Year	Value	Year	Value	Year
1	Bielsko-Biała	152	1977	90	2008	269	1957	323	2008
2	Chojnice	150	1977	100	2002	260	1977	319	1963
3	Hel	151	1951	88	2008	271	1966	354	2000
4	Jelenia Góra	158	1962	107	2002	248	1953	293	1978
5	Kalisz	140	1952	79	1999	256	1973	328	1996
6	Katowice	150	1955	100	2002	245	1956	321	1989
7	Legnica	140	1952	91	2009	250	1991	314	2001
8	Lesko	157	1958	100	1989; 2002	252	1969	307	1984
9	Łódź	151	1966	99	1963	259	1959	322	2008
10	Poznań-Ławica	147	1957	100	1961; 2008	250	1991	324	2000
11	Rzeszów	152	1977	94	1989	256	1973	316	1989; 2008
12	Słubice	151	1977	91	1961	245	2003	314	2001
13	Suwałki	161	1982	99	2002	258	1999	316	1957
14	Szczecin	148	1957	95	1983	259	1952	326	2008
15	Świnoujście	131	1978	85	1998; 2006	285	1973	362	2006
16	Toruń	152	1975	105	1998	256	1971	311	1974
17	Warszawa-Okęcie	144	1991	95	1989	269	1977	322	2008
18	Włodawa	148	1990	97	2002	254	1973	302	1974
19	Wrocław	149	1957	91	2009	250	1991	323	1961
20	Zakopane	154	1977	103	2006	246	1958	295	1980

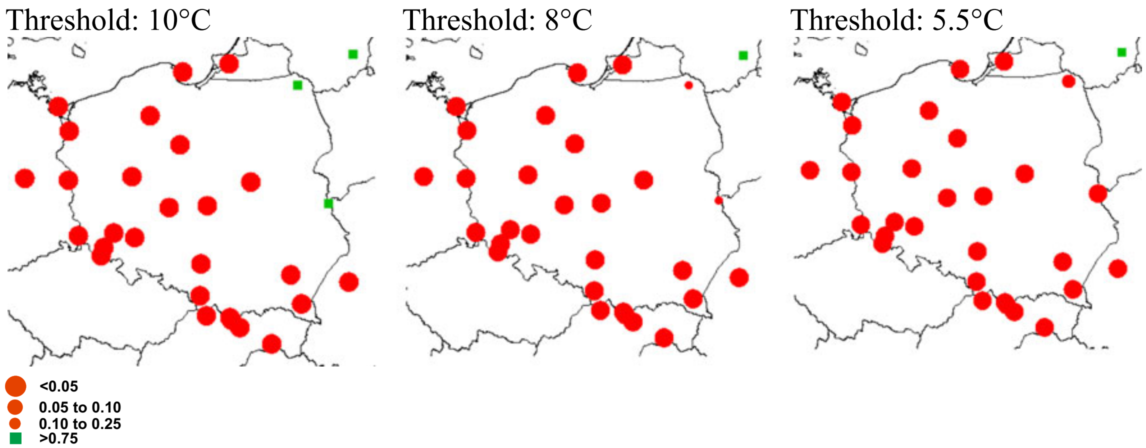

Fig. 4 Trend in changes in annual sums of GDD, for three threshold values of 10, 8, and 5.5 °C, after Mann-Kendall test

date of the first autumn frost was detected, i.e., the autumn frost comes earlier there. This is counterintuitive.

The earliest last spring frost day occurred predominantly in the 2000s (16 stations) and in particular in 2002 (6 stations) and the latest last spring frost day in the 1950s (8 stations) and in the 1970s (7 stations), in particular in 1977 (5 stations) and 1957 (3 stations). The earliest first autumn frost day occurred predominantly in the 1970s (7 stations) and in the 1950s (6 stations), but it also occurred in the 1990s (4 stations) and in the 2000s (1 station) and the latest first autumn frost day in the 2000s (9 stations), therein in 2008 at 5 stations. This is consistent with the warming, but the inter-decadal variability is

Table 4 Maximum values of annual sums of GDD, for three threshold values of 10, 8, and 5.5 °C. Values of GDD were rounded to nearest integer

No.	Station name	Threshold: 10 °C		Threshold: 8 °C		Threshold: 5.5 °C	
		Value	Year	Value	Year	Value	Year
1	Bielsko-Biała	1198	2006	1609	2006	2200	2000
2	Chojnice	1073	2006	1434	2006	1902	2002
3	Hel	1070	2006	1451	2006	2010	2006
4	Jelenia Góra	989	2002	1312	2006	1850	2006
5	Kalisz	1301	2006	1708	2006	2280	2006
6	Kasprowy Wierch	111	1994	222	2003	453	2003
7	Katowice	1203	2003	1576	2006	2141	2006
8	Legnica	1301	2003	1711	2006	2298	2006
9	Lesko	1046	1963	1355	2003	1920	2002
10	Łódź	1236	2006	1634	2006	2098	2002
11	Poznań-Ławica	1350	2006	1758	2006	2333	2006
12	Rzeszów	1220	2002	1613	2006	2170	2006
13	Słubice	1338	2006	1766	2006	2358	2006
14	Suwałki	1090	2002	1420	2002	1883	2002
15	Szczecin	1175	1992	1708	2006	2305	2006
16	Śnieżka	188	2006	331	2003	604	2006
17	Świnoujście	1162	2006	1562	2006	2152	2006
18	Toruń	1221	2006	1609	2006	2177	2006
19	Warszawa-Okęcie	1311	2006	1704	2006	2265	2006
20	Włodawa	1226	2002	1580	2002	2127	1963
21	Wrocław	1291	2006	1699	2006	2279	2006
22	Zakopane	682	1994	1054	2003	1509	2000

Table 5 Minimum values of annual sums of GDD, for three threshold values of 10, 8, and 5.5 °C. Values of GDD were rounded to nearest integer

No.	Station name	Threshold: 10 °C		Threshold: 8 °C		Threshold: 5.5 °C	
		Value	Year	Value	Year	Value	Year
1	Bielsko-Biała	625	1978	962	1978	1451	1980
2	Chojnice	540	1965	840	1987	1296	1987
3	Hel	561	1962	882	1962	1349	1965
4	Jelenia Góra	521	1978	833	1978	1292	1980
5	Kalisz	709	1980	1042	1980	1530	1980
6	Kasprowy Wierch	1	1978	18	1978	106	1978
7	Katowice	666	1978	1001	1980	1481	1980
8	Legnica	744	1978	1090	1980	1591	1980
9	Lesko	538	1978	858	1978	1340	1980
10	Łódź	661	1980	980	1980	1455	1980
11	Poznań-Ławica	734	1980	1066	1980	1560	1980
12	Rzeszów	660	1978	999	1978	1496	1978
13	Słubice	732	1962	1079	1962	1570	1962
14	Suwałki	521	1987	807	1987	1227	1987
15	Szczecin	780	1980	994	1962	1542	1965
16	Śnieżka	31	1956	78	1980	208	1980
17	Świnoujście	596	1962	933	1962	1420	1962
18	Toruń	702	1965	1003	1965	1443	1965
19	Warszawa-Okęcie	715	1978	1049	1980	1521	1965
20	Włodawa	641	1978	954	1978	1437	1978
21	Wrocław	735	1978	1081	1980	1576	1965
22	Zakopane	268	1978	495	1980	887	1978

Table 6 Numbers of stations at which statistically significant trends in temperature-related agroclimatic indices were observed, for two significance levels: 0.05 and 0.1

Index	Statistical significance: 0.05	Statistical significance: 0.1
Length of the growing season	11 of 22	14 of 22
Length of the frost-free season	15 of 22	16 of 22
Date of occurrence of last spring frost	13 of 20	15 of 20
Date of occurrence of first autumn frost	6 of 20	8 of 20
Annual sums of growing degree-days for the threshold value of 10 °C	20 of 22	20 of 22
Annual sums of growing degree-days for the threshold value of 8 °C	20 of 22	20 of 22
Annual sums of growing degree-days for the threshold value of 5.5 °C	21 of 22	*22 of 22*

strong (e.g., at some stations record cold indices were observed in the 1970s) (Table 3).

3.3 Annual sums of growing degree-days

The annual sums of GDD (also called degree-days of vegetation) were calculated for all 22 stations in Poland and for three threshold values of 10, 8, and 5.5 °C. The lowest values of this index, for the three thresholds, as noted above, occurred at high-mountain stations: Kasprowy Wierch (on average, 45, 114, and 280 degree-days, respectively, in a year) and Śnieżka (90, 190, and 398 degree-days, respectively, in a year). In the area of these stations, climate is too harsh for vegetation. Low values were also observed at a piedmont station in Zakopane (below 850, 1000, and below 1600 degree-days, respectively, in a year), in coastal stations: Hel and Świnoujście and in a south-east station, Suwałki. The highest values of GDD were observed in most lowland stations, except for northeast.

Detection of trends with the help of statistical tests in long-term time series of annual sums of GDD (Fig. 4), for three threshold values of 10, 8, and 5.5 °C, showed existence of trend on the significance level of 0.01 at 20, 20, and 21 (of 22) stations, respectively. At some stations, significance level was very high: 0.0001 (e.g., for 5.5 °C threshold at 10 stations: Bielsko-Biała, Jelenia Góra, Kalisz, Katowice, Legnica, Rzeszów, Słubice, Szczecin, Toruń, and Wrocław). The weakest significance level for 5.5 °C threshold was 0.0557 for Suwałki. In none of the analyzed series a downward trend was detected.

The highest annual sums of GDD—degree-days of vegetation (Table 4), for three temperature threshold values of 10, 8, and 5.5 °C occurred predominantly in the 2000s (18 stations for 10 °C, all 22 stations for 8 °C, and 19 for 5.5 °C). In a single record year, 2006, the highest index of GDD occurred in 12, 16, and 14 stations, respectively, for the three thresholds considered. Only for two stations the maxima occurred in the first 20 years of observations. In 1963, the maximum of GDD in Lesko for the 10 °C threshold occurred and in Włodawa for the 5.5 °C threshold.

Surprisingly, record low annual sums of GDD (Table 5) for three threshold values of 10, 8, and 5.5 °C occurred mostly not in 1950s but in two individual years, 1978 and 1980. In a single year, 1980, the lowest value of GDD occurred, respectively, in 4, 9, and 9 stations, while in 1978, the lowest index of GDD occurred, respectively, in 11, 6, and 4 stations. The minimum GDD values for all thresholds occurred in 1980 in Kalisz, Łódź, and Poznań-Ławica, while in 1978 in Kasprowy Wierch, Rzeszów, and Włodawa.

3.4 Summary of observed trends in temperature-related agroclimatic indices

The three classes of thermal indices of relevance to agriculture tackled in this paper vary in terms of the number of stations with detected significant trends (Table 6). The highest percentage of significant changes was found for three indices of the annual sums of growing degree-days for various temperature thresholds. In particular, the GDD index for the 5.5 °C threshold is significant at the 0.1 level at all the 22 stations and at the 0.05 level for all but one station (i.e., 21 out of 22). The remaining two classes of indices have a lower percentage of stations with significant changes. In particular, the change (delay) in date of occurrence of first autumn frost is significant

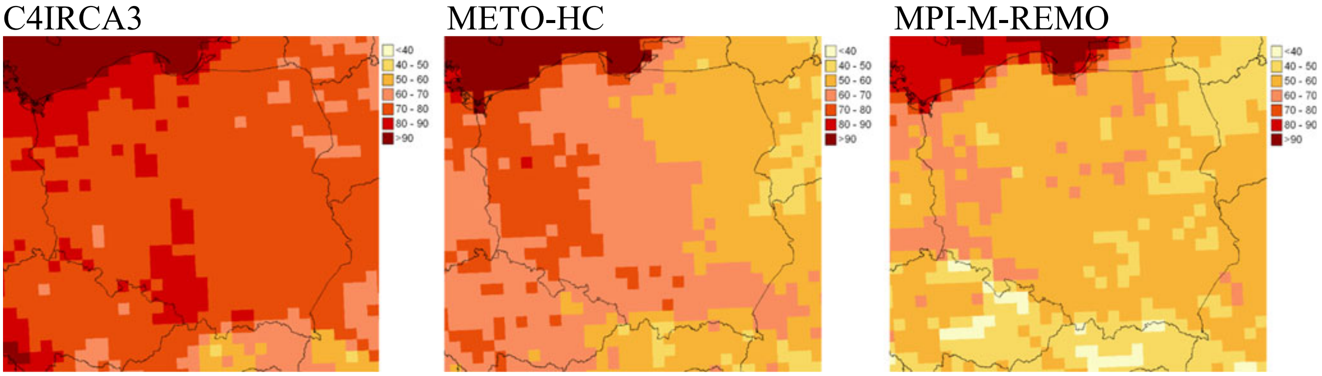

Fig. 5 Changes in growing season length—projections of three regional climate models (difference between 2061–2090 and 1961–1990)

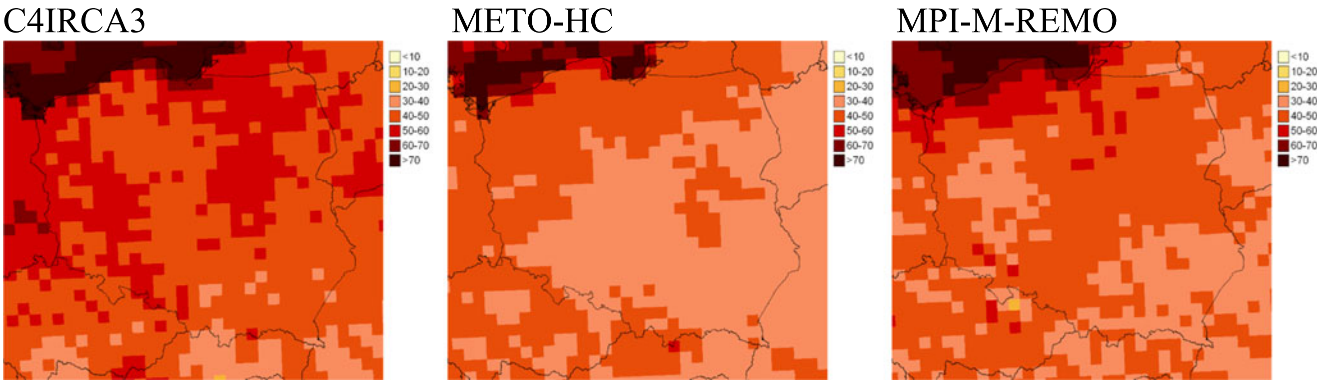

Fig. 6 Changes in frost-free season length—projections of three regional climate models (difference between 2061–2090 and 1961–1990)

at 8 stations (40 % of the total number) at the 0.1 level and at 6 stations only (30 % of the total number) at the 0.05 level.

4 Projections of changes of temperature-related agroclimatic indices

Simulations made with the help of regional climate models in the ENSEMBLES Project were used to quantify agroclimatic indices. Results from 3 of 15 available regional climate models have been chosen (Graczyk 2013) that fit best to the climate conditions in Poland (instrumental data in the control period of 1961–1990). They are MPI-M-REMO from the Max Planck Institute (Hamburg, Germany), METO-HC from the Met Office's Hadley Centre (Exeter, UK), and C4IRCA3 from the Rossby Centre (Norrköping, Sweden). The selected regional climate models with resolution about 25 km (600 cells over the territory of Poland) were forced by two different global circulation models (GCM). METO-HC and C4IRCA3 regional models were constructed based on METO-HC GCM, whereas MPI-M-REMO was driven by the 5th generation of the ECHAM GCM (cf. Szwed et al. 2010). Model-based simulations were considered for two future time horizons, a century apart, i.e., 1961–1990 and 2061–2090, for SRES A1B scenario (Nakicenovic et al. 2000).

On average, the growing season is projected to increase, depending on a model, by 40–60 days in the east of Poland and even by 70–90 days on the west (Fig. 5), where it will increase to nearly 300 days in a year. In the northeast of Poland, where the vegetation season is shortest, it will exceed 250 days (average from three models for the Suwałki area). According to one of the models (C4IRCA3), in warmest years, the growing season is projected to last nearly whole year (over 350 days) over most of Poland.

According to three models, the frost-free season will lengthen by 40–70 days. The increase will be highest where the frost-free season is at its shortest now. This also means that the date of occurrence of the last spring frost and the first autumn frost will be shifted. According to projections, based on the MPI-M-REMO simulations, the frost-free season will lengthen in western Poland by less than 40 days (Fig. 6).

The spring frost in Poland will end between the 50th and the 110th day of the year, depending on a model and a region. In the Baltic coast, the last spring frost will occur earliest in February and in foothills and east of Poland latest in mid-April. Similarly, the first autumn frost will be delayed, occurring between mid-October and beginning of December.

Projected changes for 2061–2090 in GDD for all three temperature thresholds considered, i.e., 10, 8, and 5.5 °C, defined with reference to the control period 1961–1990

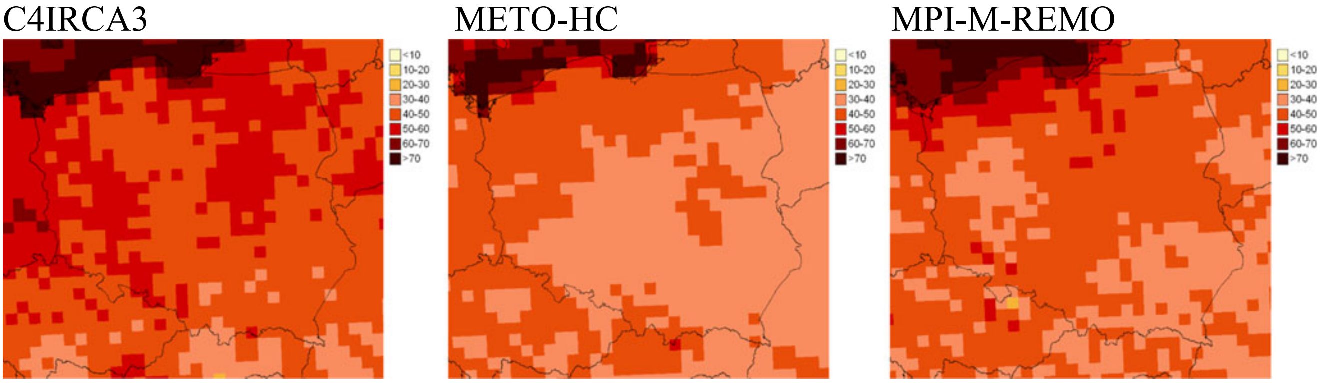

Fig. 7 Changes in growing degree-days (GDD) for the 10 °C threshold—projections of three regional climate models (difference between 2061–2090 and 1961–1990)

demonstrate regular increases. For 10 °C threshold (Fig. 7), according to the C4IRCA3 and the METO-HC models, the mean GDD values will increase by more than 500 degree-days over a large area of Poland. In projections by the MPI-M-REMO model, the changes are lower than in simulations by other models—in the belt covering most of Poland, the increase should not exceed 400 degree-days. For 8 °C threshold, the largest increase, according to the METO-HC model, exceeding 800 degree-days, is possible in the south and southwest of Poland. For 5.5 °C threshold, the increase exceeds 1000 degree-days in the METO-HC model projections.

5 Discussions and conclusions

The analysis reported in this paper sheds light on the behavior of the time series of seven indices at 22 meteorological stations in Poland, spanning the interval of 1951–2010. Trend detection was carried out, with the help of the Mann-Kendall test.

Consistently with the warming, an increase in "warm" indices has been observed, such as the lengths of the growing season and of the frost-free season, the date of occurrence of first autumn frost, and the annual sums of growing degree-days for three temperature threshold values. The date of occurrence of last spring frost, i.e., where increase would correspond to cooling, has decreased, consistently with the warming.

As expected, detected changes correspond to the overwhelming and ubiquitous warming. However, strong natural variability is noted; hence, the trends are not of ubiquitous statistical significance. Nevertheless, for no station and no index, a statistically significant trend (significance level ≤ 0.05) corresponding to cooling was noted in Poland.

The highest values of "warm" indices have been observed, with few exceptions, in the last two decades analyzed, 1991–2010.

These results are consistent with the studies of thermal characteristics of importance to agriculture in Poland, Europe, and other continents. Extension of the thermal growing season has been observed for many areas, with use of different observation periods and calculation methods (Carter 1998; Menzel et al. 2003; Żmudzka 2004; Linderholm 2006; Linderholm et al. 2008; Dong et al. 2013). This is also confirmed by phenological observations in some regions (Menzel 2000; Chen et al. 2005; Lou et al. 2013).

Changes of thermal characteristics associated with the occurrence of frost, in line with those described in this paper, have been identified by Menzel et al. (2003), Kunkel et al. (2004), and Bielec-Bąkowska and Piotrowicz (2011).

Changes in growing degree-days presented in this research are consistent with the results of other studies, in which an increase of this indicator has been also observed for different values of temperature thresholds (Kadioglu and Saylan 2001; Feng and Hu 2004; Żmudzka 2012).

Based on our analysis of projections via climate models, further improvement of thermal characteristics of importance to agriculture can be expected, even if the first autumn frost can come quite early even in the warmer climate.

Nevertheless, this paper only deals with temperature-related agroclimatic indices. Here, all thermal changes (*ceteris paribus*) look beneficial for agriculture. However, such an observation would be misleading, because of other factors driving crop yield. It is likely that changes in yield will be driven by hydrothermal conditions: advantageous changes in temperature and disadvantageous changes in availability of soil moisture. Indeed, the water availability can be a limiting factor. The seasonal distribution of precipitation has already adversely changed (the ratio of precipitation total in warm half-year to precipitation total in cold half-year has decreased) and even stronger adverse changes are projected in the future (Pińskwar 2010). This is so, because of likely increase of frequency, intensity, and duration of soil moisture droughts as well as of intense precipitation and flooding, even if models are not in agreement to quantitative changes in projections of spring and summer precipitation. Longer periods with soil moisture deficit (and inadequate water availability potential for massive irrigation) will likely be interspersed by intense precipitation episodes.

The results obtained in this study are of considerable societal and economic importance. Improving the insight and understanding of changes in agroclimatic indices is relevant and timely.

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