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*Regular research paper*

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# CONTEMPORARY CHANGES OF CLIMATE IN POLAND: TRENDS AND VARIATION IN THERMAL AND SOLAR CONDITIONS RELATED TO PLANT VEGETATION

ABSTRACT: Presented paper analyses climate trends in Poland in the second half of the 20th century. Measurements of climate elements were obtained from 5 meteorological stations evenly distributed over Poland (Szczecin 53°24'N–14°37'E, Wrocław 51°08'N–16°59'E, Łódź 51°44'N–19°24'E, Suwałki 54°08'N–22°57'E, Przemyśl 49°48'N–22°46'E). The variability of several indices conditioning the growth of plant vegetation was determined. Increase in the air temperature in the first three quartiles of the calendar year was detected. During November–December period the opposite tendencies were noted, however not statistically significant.

The length of winter period shortened considerably, especially in western Poland. The warming caused substantial rise in potential evapotranspiration, the largest in April, May and August. Summer period has extended during the last five decades. Cumulative temperatures, calculated with respect to the 10°C threshold, also revealed an upward tendency.

Sunshine duration totals increased – the highest increase was observed in the western Poland in May–June season. The length of vegetation season (> 5°C) did not change significantly during the 50-year period. There was only a slight tendency towards the earlier occurrence of both beginning and ending date of this season.

The climate transformation in Poland, related undoubtedly to global warming, indicates possible intensification of vegetation growth due to more favourable solar and thermal conditions.

KEY WORDS: climate changes in Poland, vegetation season, thermal seasons, climatic water balance, evapotranspiration

## 1. INTRODUCTION

Climate of Poland has changed remarkably during the last decade of the 20th century compared with climatological standard normals calculated for the earlier periods. Considerable warming occurred during the first half of the calendar year (Kożuchowski and Żmudzka 2001a, see Table 1). Winters became milder and mostly lacking in persistent snow cover. Spring has become warmer than autumn. Recently, extremely hot summers have also been noted. From among ten maximum values of mean annual temperature recorded in the period 1951–2000 in Poland, six of them occurred during the last decade of the 20th century. The course of the air temperature in the years 1951–2000 shows an increasing rate of warming in Poland, which may correspond to the well-known global warming proceeding in this period (Degirmendžić *et al.* 2004). Increasing frequency is the feature that also characterises the occurrence of thermal anomalies in Europe (Kysely 2002). For instance, year 1999

Table 1. Differences between mean monthly air temperatures in Poland averaged for the period 1991–2000 and climatological standard normal 1931–1960, absolute (Δ) and standardised (Δ/SD) differences. SD – standard deviation. Areal means of temperature, averaged for 29 meteorological stations evenly distributed within Poland's borders, were used (from Kożuchowski and Żmudzka 2001a).

| Month | Δ (°C) | Δ/SD |
|---|---|---|
| Jan | 2.4 | 0.75 |
| Feb | 2.3 | 0.67 |
| Mar | 1.7 | 0.74 |
| Apr | 1.2 | 0.71 |
| May | 0.3 | 0.20 |
| Jun | 0.0 | 0.03 |
| Jul | 0.2 | 0.16 |
| Aug | 0.6 | 0.53 |
| Sep | −0.2 | −0.11 |
| Oct | 0.4 | 0.22 |
| Nov | −0.4 | −0.18 |
| Dec | −0.2 | −0.09 |
| Year | 0.7 | 0.88 |

was the warmest over the territory of Great Britain and Holland within 341 and 294-year period of instrumental measurements, respectively (Annual Bulletin... 1999).

Average air temperature for the year 2000 reached the unprecedented level in the period of instrumental measurements spanning more than 200 years (Kożuchowski and Żmudzka 2001a). The average temperature in this specific year in central Poland (Warsaw) equalled 10.1°C. The first several years of the 21st century were also relatively warm and exceeded the long-term average (7.8°C). In Warsaw mean annual temperatures equal 9.1, 9.9 and 8.3°C were noted in year 2001, 2002 and 2003, respectively. Those years were also crucial for a warming course on a global scale. In September 2002 the area of Arctic ice cover was the smallest than ever recorded. Additionally, during this year 2003 summer was extremely hot in western Europe. In France, Italy, the Netherlands, Portugal, Spain and the United Kingdom over 21000 deaths were related to the unrelenting heat (World Climate News 2004).

The progressive warming may cause significant changes in the environment. It may affect plants growth and change the intensity of the hydrological cycle and other processes proceeding in ecosystems. However, it is worth emphasising that climatic changes observed so far in Poland are specific. The appreciable rise in mean annual temperatures does not correspond to the prolonging of the vegetation period. Moreover, the observed spring warming does not influence the hydrological balance since simultaneous increase of precipitation is noted. The growing season in Poland extended by merely 5 days during the years 1951–2000 on average (Żmudzka 2004). Statistically significant upward trend in precipitation totals in March was also detected in this period while annual sums remained nearly the same (Degirmendžić *et al.* 2004).

The results of the long-term phenological observations justify the statement that the length of growing season was relatively stable until the year 1990 (Tomaszewska and Rutkowski 1999). The length of the growing period lasting from the onset of spring (the blossoming period of *Corylus avellana*, *Salix carpea* and others) till the end of autumn (yellowing of leaves of *Aesculus hippocastanum*, *Betula verrucosa* leaf fall) did not show important changes during the successive decades of the period 1951–1990. Only the slight tendency towards earlier occurrence of plant first vital processes in spring is noticeable. Phenological observations are reflected in the variability of climatological records – the current thermal seasons start earlier than the former ones (Kożuchowski *et al.* 1999). Above-mentioned relatively stable duration of the vegetation season differentiates Poland from other countries situated to the west and south of Poland, where most data concerning phenological phases comes from. These phases are monitored in the so-called phenological gardens (International Phenological Gardens IPG). According to Menzel (2000) vegetation season prolonged by almost 11 days in Europe in the period 1959–1996 as a result of both earlier spring onset (6.3 days) and the delay of the autumn cooling (4.5 days). However, in Poland, simultaneously with the advancing of the beginning date of vegetation season, ending date advances. As a consequence, the length of growing season did not change distinctly.

The aim of present work is to determine changes of climate characteristics in Poland during the second half of the 20th century, which can affect the period and intensity of plant vegetation.

## 2. MATERIAL AND METHODS

The analysis is based on indices, which evaluate the character and intensity of thermal stimuli and the response of vegetation. We analyse not only the variation of the length of vegetation period, i.e. season characterised by the mean daily temperature above 5°C, but also changes of the length of thermal winter (<0°C) and summer (> 15°C) periods and the course of cumulative temperature. The last index is expressed in degree–days and describes the accumulated excess of temperature above a given standard temperature. The thresholds 5°C and 10°C were applied in present analysis. The frequency of crossing the 0°C level was also calculated. This index evaluates the frequency of soil freezing-defrosting processes. The 50-year trends of the air temperature were calculated for each decade. Trend coefficients inform about the transformation of the annual cycle during the analysed period.

Day-to-day changes of temperature superimposed on the annual cycle cause some difficulties in determining the exact date of the beginning and the end of thermal seasons and vegetation period. These closing dates were fixed with the help of the method proposed by Huculak and Makowiec (1977), commonly used in climatological analysis (e.g. Żmudzka 2003a, b, 2004; Żmudzka and Dobrowolska 2001). According to the principal assumption of Huculak-Makowiec's method, the beginning of thermal season is set by the date after which the cumulative values of the subsequent deviations from a given thermal threshold are only positive (in the ascending phase of the annual cycle, i.e. during spring and summer) or negative (in the descending part of the cycle, i.e. in autumn and winter). 0°C constitutes thermal threshold for winter, 5°C for growing season and spring, 15°C for summer and autumn.

Temperature fluctuations have considerable impact on the evapotranspiration – significant climate factor shaping the environmental conditions. The long-term changes of the potential evapotranspiration were estimated. In order to calculate the potential evapotranspiration, the method of Doroszewski and Górski (1995) was applied. According to their formula, the potential evapotranspiration (*Em*, in mm) is a function of monthly average temperature (*Tm*, in °C), monthly sum of sunshine duration (*Hm*, in hours) and the length of the day in the middle of a given month (*fm*, in hours):

$$E_m=0.0621 \cdot T_m^2+0.00448 \cdot H_m^{1.66}+9.1 \cdot f_m-89.6 \qquad (1)$$

The present analysis was performed on the basis of daily mean temperatures from five meteorological stations: Łódź situated in central Poland, Szczecin, Wrocław, Suwałki and Przemyśl representing peripheral regions of the country – NW, SW, NE and SE respectively (Fig. 1). All five meteorological stations used in the study are monitored by Polish Institute of Meteorology and Water Management and supervised by World Meteorological Organisation. The homogenity of the measurement series at individual stations was tested by means of the Alexandersson test (Alexandersson 1986).

Temperature records cover the period 1951–2000. Records of sunshine duration cover the period 1971–2000 in case of four peripheral meteorological stations and 1951–2003 in case of Łódź. The formula (1) was verified by Doroszewski and Górski (1995) for western and central Poland. Standard error of $E_m$ estimation, calculated for warm season of the year (April–October), works out at 5.3 mm.

The comparison was made between trend coefficients of selected climate characteristics calculated for the whole 50-year period and the last decade (1991–2000).

## 3. RESULTS

### 3.1. Length of vegetation season

Thermal vegetation season in Poland in the years 1951–2000, determined on the


Fig. 1. Outline of Poland with the location of five meteorological stations in NW (Szczecin), SW (Wrocław), NE (Suwałki), SE (Przemyśl) and central Poland (Łódź).

basis of 5°C threshold, lasted from the 31st of March till the 4th of November on average (Żmudzka 2004). Thereby its duration is equal to 219 days. Western and southern regions of the country (Wrocław, Szczecin, Przemyśl) are characterised by more favourable conditions for plant growing than north–eastern Poland (Suwałki) where the most harsh conditions exist (Table 2).

Tendency toward earlier occurrence of starting and ending date of the vegetation season was a characteristic feature of the last decade of the 20th century. As a result of such thermal regime transformation the length of the growing season remained almost unchanged. Only a slight prolonging of vegetation period may be observed in the western part of Poland while opposite tendency is noted in the eastern and central regions. Żmudzka and Dobrowolska (2001) came to the similar conclusions. They studied the changes of growing season length on the basis of the data obtained from 51 meteorological stations in Poland. Chmielewski and Rötzer (2000) show that slight cooling took place in south-eastern Europe and the onset of the vegetation season delayed during the last 30 years of the 20th century. On the contrary, over central and western Europe the duration of the vegetation period is increasing. According to these authors mean annual temperature rise by 1°C corresponds to the lengthening of the growing season by 5 days. It is worth noticing, however, that this relationship depends on temperature trends in particular seasons. Warming in Poland, especially in the eastern part of the country, as it is presented further in the text, occurred

Table 2. Average dates of starting and ending points and duration time of the vegetation season in the period 1951–2000 and their changes in the decade 1991–2000 ("–" denotes earlier and "+" later occurrence).

| Region (station) (see Fig. 1) | Mean characteristics for the period 1951–2000 | | | Change in the period 1991–2000 | | |
|---|---|---|---|---|---|---|
| | Beginning date | Ending date | Duration (days) | Beginning (days) | End (days) | Duration (days) |
| NW (Szczecin) | 21 Mar | 13 Nov | 238 | −12 | −7 | +5 |
| SW (Wrocław) | 22 Mar | 10 Nov | 234 | −4 | −7 | −3 |
| Central (Łódź) | 31 Mar | 5 Nov | 220 | +2 | −8 | −10 |
| NE (Suwałki) | 11 Apr | 29 Oct | 202 | −1 | −1 | 0 |
| SE (Przemyśl) | 26 Mar | 9 Nov | 229 | +6 | −3 | −9 |

Table 3. Trends of starting and ending date and duration time of vegetation season in the period 1951–2000 (days decade$^{-1}$). Coefficients significantly different from 0 at 0.05 level are in bold.

| Region (station) (see Fig. 1) | Beginning | End | Duration |
|---|---|---|---|
| NW (Szczecin) | **−0.70** | −0.18 | **0.50** |
| SW (Wrocław) | **−0.35** | **−0.24** | 0.13 |
| Central (Łódź) | −0.22 | **−0.24** | −0.02 |
| NE (Suwałki) | −0.14 | −0.01 | 0.05 |
| SE (Przemyśl) | −0.08 | −0.12 | −0.05 |

mainly in winter and summer, therefore did not influence the length of the vegetation season. Szczecin makes an exception and reveals distinct tendencies, as described by Chmielewski and Rötzer (2000).

"Anomalies" observed in the years 1991–2000 may be interpreted as a result of the long-term tendencies proceeding during the whole half-century period. Significant trend of the starting date in north-western (Szczecin) and south-western Poland (Wrocław) as well as the ending date of growing season in SW and central Poland (Łódź) was observed during this period (Table 3). The trend coefficients show the earlier beginning and end of growing season. Considerable prolonging of vegetation period was detected only in the north-west (Szczecin). The rest of analysed records remained insignificant and indeterminate, as regards to their tendencies and direction (Table 3). The rate of advancing of the beginning date of the vegetation season as well as trend coefficient of its duration in the north-west (Szczecin) in the period 1951–2000 were half as large as corresponding rates assessed for the territory of Germany by Menzel *et al.* (2003) −0.7/−1.3 and 0.5/1.1 days $10^{-1}$ years, respectively (see Table 3).

Observed warming has affected vegetation conditions slightly. The growing season prolonged only a few days in the warmest region of the country. More effective prolonging was limited by earlier autumn.

### 3.2. Thermal summer season and cumulative temperatures

Thermal summer, i.e. the period with temperatures exceeding 15°C, starts at the end of May and finishes in the first decade of September, on average. The north-eastern part of Poland makes an exception – summer in this region ends usually during the last days of August. The duration of thermal summer period in Poland has prolonged. Summer lasted by ca. 5–10 days longer in the last decade of the 20th century than in 50-year period on average (Table 4).

The lengthening of thermal summer period corresponds with global warming that proceeds in spring months and in August. The warming rate is also estimated for the record of cumulative temperatures calculated with respect to 0, 5 and 10°C level, with the help of the method recommended by Trojan (1977, 1985) and widely used by contemporary climatologists (e.g. Glickman 2000). The surplus of cumulative temperatures was detected in every region of Poland during the last decade of the 20th century (Table 5). The most significant difference, that exceeded by 10% the mean for 50-year period, was detected in case of temperatures higher than 10°C.

As opposed to insignificant changes of the length of vegetation period, a very large increase of "heat reservoir" was observed in the last decade of the 20th century. The analysis of meteorological records revealed that in the last years the warming up has also occurred in summer, besides significant temperature increase in winter, and caused specific changes in the environment. It was shown that upward trend of temperature in

Table 4. Mean duration of thermal summer season (> 15°C) in the period 1951–2000 and its changes in the decade 1991–2000.

| Region (station) (see Fig. 1) | Averages for the period 1951–2000 (days) | Change in the decade 1991–2000 (days) |
|---|---|---|
| NW (Szczecin) | 108 | +7 |
| SW (Wrocław) | 114 | +10 |
| Central (Łódź) | 98 | +9 |
| NE (Suwałki) | 95 | +9 |
| SE (Przemyśl) | 111 | +5 |

Table 5. Mean annual cumulative temperatures in the period 1951–2000 and their changes in the decade 1991–2000.

| Region (station) (see Fig. 1) | Sum of temperature > 0°C (degree-days) | | Sum of temperature > 5°C (degree-days) | | Sum of temperature > 10°C (degree-days) | |
|---|---|---|---|---|---|---|
| | 1951–2000 | 1991–2000 | 1951–2000 | 1991–2000 | 1951–2000 | 1991–2000 |
| NW (Szczecin) | 3483 | +215 | 2079 | +163 | 1056 | +129 |
| SW (Wrocław) | 3539 | +262 | 2159 | +229 | 1133 | +187 |
| Central (Łódź) | 3168 | +129 | 1882 | +106 | 932 | +84 |
| NE (Suwałki) | 2947 | +187 | 1773 | +153 | 895 | +125 |
| SE (Przemyśl) | 3326 | +203 | 2048 | +169 | 1068 | +139 |

spring and early summer is correlated with Normalised Difference Vegetation Index (*NDVI*) averaged for the territory of Poland (Kożuchowski 2000, Kożuchowski and Żmudzka 2001b). This index employs the difference formula *NDVI = (NIR — VIS)/(NIR + VIS)* where *VIS* and *NIR* are the visible and near-infrared radiation reflected by vegetation (Justice *et al.* 1985). Healthy vegetation absorbs most of the visible light that hits it and reflects a large portion of the near-infrared light – in that case *NDVI* is close to +1. Unhealthy or sparse vegetation reflects more visible and less near-infrared radiation that lowers *NDVI* values. Menzel (2000) also points out that there is a good correlation between the change of climate conditions and vegetation development determined by *NDVI* index. Tucker *et al.* (2001) estimated the rate of the advancing of the beginning date of the growing season at 3.5 days. His analysis was based on *NDVI* index calculated for the Northern Hemisphere (north of 35°N) and limited to the years 1982–99.

### 3.3. Thermal winter season and 0°C threshold passage

The most significant climate changes are observed in winter (<0°C). This season is characterised by the largest temperature variations. In fact, thermal winter started quite early during the last decade of the 20th century but its duration shortened considerably. In north-western Poland (Szczecin) the length of winter season decreased by half of its average duration in 50-year period (Table 6). Furthermore, years with the lack of winter became more common or, which is even more characteristic of the end of the century, winter period has split into two or three cold subperiods separated by thaws. Winter season terminated by the distinct and

Table 6. Mean duration of thermal winter (<0°C) in the period 1951–2000 and its changes in the period 1991–2000.

| Region (station) (see Fig. 1) | Averages (1951–2000) (days) | Change (1991–2000) (days) |
|---|---|---|
| NW (Szczecin) | 41 | −20 |
| SW (Wrocław) | 50 | −16 |
| Central (Łódź) | 77 | −5 |
| NE (Suwałki) | 100 | −12 |
| SE (Przemyśl) | 78 | −14 |

Table 7. The number of years with "coreless"* winter (CLW) and with the lack of thermal winter (LW) in the successive decades of the period 1951–2000 in different parts of Poland (see Fig. 1).

| Decades | NW (Szczecin) | | SW (Wrocław) | | Central (Łódź) | | NE (Suwałki) | | SE (Przemyśl) | |
|---|---|---|---|---|---|---|---|---|---|---|
| | CLW | LW | CLW | LW | CLW | LW | CLW | LW | CLW | LW |
| 1951–1960 | | | 1 | | | | | | | |
| 1961–1970 | 3 | | 1 | | | | | | | |
| 1971–1980 | 1 | | 2 | 1 | 1 | | 1 | | | |
| 1981–1990 | 1 | 3 | 1 | 2 | 2 | | 1 | | 3 | |
| 1991–2000 | 2 | 4 | 4 | 1 | 2 | | 1 | | 2 | |

* winter season that splits into two or three cold subperiods separated by thaws.

long-lasting warming up is called "coreless" winter – this term derives from polar climatology.

Together with thermal winter disappearance the "coreless" winters started to occur more often during the several successive decades of the past century (Table 7). During the last decades "coreless" winter occurred even in the eastern part of Poland.

Although the "coreless" winters have become more common phenomena recently, the frequency of the 0 °C threshold passage did not change significantly at the end of the century (Table 8). It is the result of the rise in mean winter temperature and the preservation of temperature variability pattern – winters became shorter and milder. There was a decrease in the number of days within the year with negative temperature. The largest decline in the number of freezing days was noted in the northern part of the country, where the impact of atmospheric circulation, expressed by the advection of maritime air masses, is the strongest. Winter warming was less evident in southern Poland. The harshness of winters in this region did not change significantly. The lack of distinct temperature trend was also observed further south – for the territory of Hungary – by Domonkos and Piotrowicz (1998). Scheifinger *et al.* (2002) drawn important conclusion concerning circulation impact on thermal conditions and phenological phases in Europe. They claim that since 1980s the influence of NAO index (i.e. meridional pressure gradient over the Atlantic) on the climate of central and western Europe was limited due to the northerly shift of zone of westerlies. This shift is associated with the change of winter precipitation – many authors underline that positive trends in precipitation are observed in northern Europe while in the southern part of the continent the opposite tendencies prevail (e.g. Domonkos 2003, Schmith 2001, Niedźwiedź and Twardosz 2004).

### 3.4. Trends in the air temperature and their seasonal changes

Warming rate in Poland, estimated for the second half of the 20th century, pronounces characteristic annual cyclic pattern. The annual cycle of the air temperature change consists of several warming and cooling phases of different rates. The temperature rise in early January, at the end of February and in April (Table 9) is specific for the last decade of the 20th century. Additionally, the warming up was observed during the onset and in the middle of summer season, separated by a noticeable temperature decrease falling on the third decade of June. This recurrent phenomena, called "European monsoon", gradually becomes a peculiarity in the annual cycle of the temperature (Fortuniak *et al.* 1998). Early onset of winter, typical for the last several years, manifests in negative temperature deviations in November. Successive cooling at the end of December may eliminate "Christmas thaw" (Table 9) – peculiarity, so far clearly marked in the annual course of the air temperature.

Trends of 10-day average values of temperature correspond to above-mentioned warming and cooling episodes (Fig. 2). It is worth noting that cooling in autumn has occurred mainly in the southern Poland (Przemyśl, Wrocław) and also in central region (Łódź). Temperature fall in autumn was barely detectable in the north-west (Szczecin). In the west (Szczecin, Wrocław), upward trends predominated in the three quarters of the calendar year meaning equally strong warming in winter, spring and summer. In the north-east (Suwałki) the largest temperature rise was noted in winter (Fig. 2).

The last decade of the 20th century was characterised by slightly lower annual amplitude of temperature – it differs from the 50-year period average by several decimal points of Celsius degree (here, amplitude is defined traditionally as a difference between maximum and minimum mean monthly temperature). The change of another thermal index, calculated as a difference between spring and autumn temperature, was of considerably greater extent – it reached 0.8–1.3°C. Spring, as pointed earlier, became warmer than autumn. It should be stressed that the change of difference between spring and autumn temperature is more important with regards to its statistical significance than the change of amplitude derived only from two monthly averages. Taking this into consideration, the strengthening of thermal

Table 8. Average frequency of 0°C daily temperatures threshold passage in the period 1951–2000 and its changes in the decade 1991–2000 (number of passages year$^{-1}$).

| Region (station) (see Fig. 1) | Average (1951–2000) | Change (1991–2000) |
|---|---|---|
| NW (Szczecin) | 22 | −2 |
| SW (Wrocław) | 24 | −2 |
| Central (Łódź) | 26 | −2 |
| NE (Suwałki) | 28 | +2 |
| SE (Przemyśl) | 25 | 0 |

Table 9. Deviations of mean daily temperatures (°C) in the period 1991–2000 from the 50–year average (1951–2000) in selected phases of temperature annual cycle (in brackets – dates of the maximum absolute value of deviation).

| Region (station) (see Fig. 1) | a | b | c | d | e | f | g | h |
|---|---|---|---|---|---|---|---|---|
| NW (Szczecin) | 3.6 (10 Jan) | 3.2 (28 Feb) | 5.5 (24 Apr) | 2.6 (10 Jun) | −1.4 (24 Jun) | 2.8 (21 Jul) | −1.9 (23 Nov) | −1.4 (25 Dec) |
| SW (Wrocław) | 5.6 (10 Jan) | 3.4 (27 Feb) | 4.2 (24 Apr) | 2.7 (10 Jun) | −1.1 (24 Jun) | 3.1 (4 Aug) | −2.4 (23 Nov) | −2.0 (28 Dec) |
| Central (Łódź) | 4.6 (10 Jan) | 3.2 (27 Feb) | 4.0 (28 Apr) | 2.0 (11 Jun) | −2.1 (25 Jun) | 2.3 (3 Aug) | −2.0 (20 Nov) | −2.1 (25 Dec) |
| NE (Suwałki) | 4.6 (7 Jan) | 4.3 (24 Feb) | 4.2 (24 Apr) | 3.1 (11 Jun) | −2.2 (24 Jun) | 2.6 (3 Aug) | −2.1 (10 Nov) | −2.8 (27 Dec) |
| SE (Przemyśl) | 4.6 (8 Jan) | 3.6 (27 Feb) | 3.1 (28 Apr) | 3.1 (11 Jun) | −1.4 (25 Jun) | 2.7 (31 Jul) | −2.5 (1 Dec) | −3.0 (29 Dec) |

a – winter warming, b – early spring warming, c – spring warming, d – early summer warming, e – monsoon cooling, f – summer warming, g – early winter cooling, h – Christmas cooling.

continentality, rather than amplifying the oceanic regime, is more likely to proceed in the last decade of the 20th century. The last process dominated in the 1970s and 1980s when the decline of the annual amplitude of temperature and the intensification of zonal circulation were observed.

### 3.5. Sunshine duration

The increase of actual sunshine duration characterises contemporary changes of solar regime in Poland (Table 10). Trend coefficients are diversified seasonally and spatially. Over SW region (Wrocław) sunshine duration sums increased by 392.1 h in annual values. The largest increase occurred in May – 79.4 h. In SW region positive trends of sunshine duration are observed in all months except for September and October. Other meteorological stations experience similar tendencies in May–July season. During the remaining part of the year opposite trends of sunshine duration are observed. However, negative tendencies are statistically insignificant (Table 10).

Changes of actual sunshine duration sums in Poland show distinct meridional pattern. In western and central part of the country (Wrocław, Szczecin, Łódź – see Fig. 1) upward tendencies predominate, while in the east (Przemyśl, Suwałki), changes are not clearly determined. It is worth noting however that monthly sums of sunshine duration are getting smaller during the cold half-year in eastern Poland (Table 10).

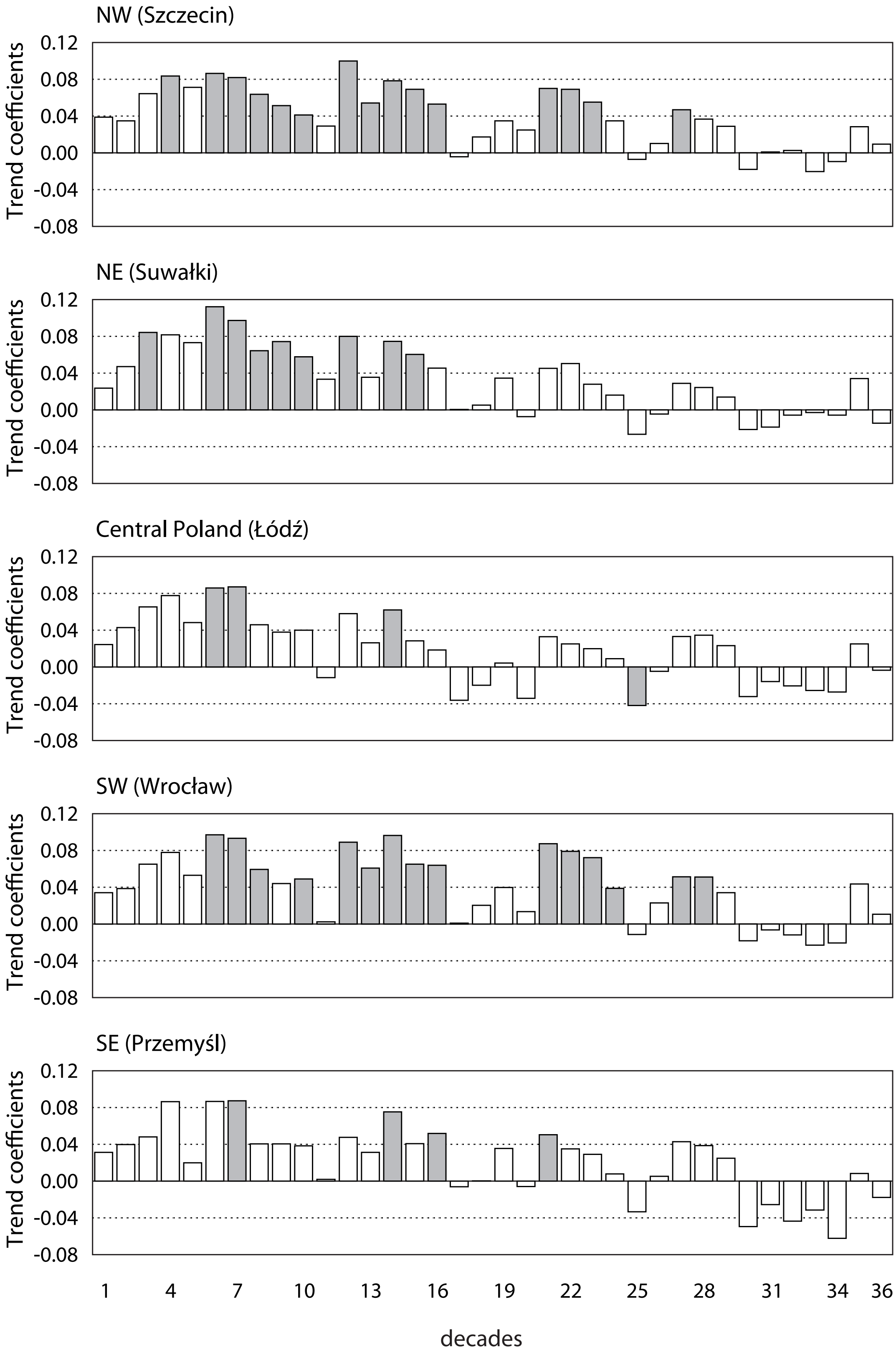


Fig. 2. Linear trend coefficients of decadal mean temperatures calculated for the period 1951–2000 (°C year$^{-1}$) in different parts of Poland (see Fig. 1). Values significant at 0.05 level are shaded.

Table 10. Trends of monthly and annual totals of actual sunshine duration (h 30 years$^{-1}$) in the period 1971–2003. Significant coefficients at 0.05 level are in bold.

| Region (station) (see Fig. 1) | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Year |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| NW (Szczecin) | **15.6** | 20.3 | 23.4 | 29.8 | 41.5 | 28.6 | 24.7 | 16.3 | 23.0 | 29.6 | 12.7 | **13.4** | **279.0** |
| SW (Wrocław) | −15.0 | −17.0 | 3.3 | −0.7 | 36.4 | 21.5 | 26.8 | 4.5 | 2.8 | −4.7 | −3.5 | −6.6 | 47.8 |
| Central (Łódź) | −0.8 | 7.7 | −0.1 | 9.1 | **47.2** | 9.0 | 12.3 | 21.1 | −5.4 | 6.4 | 4.2 | 3.4 | 114.1 |
| NE (Suwałki) | **26.3** | 23.7 | 12.0 | 33.8 | **79.4** | **78.9** | 53.3 | **56.3** | −7.3 | −1.1 | 3.9 | 15.2 | **392.1** |
| SE (Przemyśl)* | −5.1 | 13.3 | −31.2 | 33.1 | 51.1 | 43.7 | 41.5 | −13.2 | −20.8 | 8.9 | −14.6 | −9.1 | 55.7 |

* data from the period 1971–2000 was used.

Table 11. Linear trends of monthly and annual sums of actual sunshine duration (h 30 years$^{-1}$) in central Poland (Łódź) in the periods: 1951–2003 and 1971–2003. Significant coefficients at 0.05 level, according to the F-test, are in bold.

| Month | Period | |
|---|---|---|
| | 1951–2003 | 1971–2003 |
| Jan | 6.22 | −0.8 |
| Feb | 11.1 | 7.7 |
| Mar | −4.81 | −0.1 |
| Apr | 4.71 | 9.1 |
| May | **48.2** | **47.2** |
| Jun | 1.42 | 9.0 |
| Jul | 19.7 | 12.3 |
| Aug | 30.6 | 21.1 |
| Sep | −19.9 | −5.4 |
| Oct | −1.29 | 6.4 |
| Nov | 7.08 | 4.2 |
| Dec | 5.71 | 3.4 |
| Year | 108.8 | 114.1 |

In order to verify the persistence of trend evaluated on the basis of 33-year period (1971–2003), the comparison was made to trend coefficients calculated for Łódź for the 53-year period (1951–2003). Trends were estimated on the basis of monthly and annual totals (Table 11). It should be stressed that positive tendency in May constitutes significant and persistent feature of solar regime transformation in Poland. Trend coefficient calculated for longer period (53 years) remained almost unchanged, ca. 47–48 h per 30 years.

### 3.6. Evaporation during the warm season of the year

The changes of temperature and sunshine duration determine the rate of evapotranspiration and obviously affect the range of the potential evapotranspiration index ($E_m$) (1). Average $E_m$ values differ slightly over the area of Poland during the warm season of the year (Apr–Oct) (Table 12). Potential evapotranspiration increased in the 25-year period at the end of the 20$^{th}$ century. Seasonal sums rose significantly in SW (Wrocław), NE (Suwałki)

Table 12. Average values of potential evapotranspiration index ($E_m$) in the period 1976–2000 (in mm).

| Region (station) (see Fig. 1) | Apr | May | Jun | Jul | Aug | Sep | Oct | Sum Apr–Oct |
|---|---|---|---|---|---|---|---|---|
| NW (Szczecin) | 64 | 109 | 117 | 120 | 101 | 54 | 24 | 589 |
| SW (Wrocław) | 62 | 104 | 113 | 118 | 101 | 55 | 27 | 580 |
| Central (Łódź) | 60 | 104 | 113 | 117 | 98 | 52 | 16 | 559 |
| NE (Suwałki) | 62 | 110 | 123 | 122 | 100 | 51 | 19 | 586 |
| SE (Przemyśl) | 58 | 97 | 113 | 118 | 97 | 54 | 24 | 561 |

Table 13. Trend coefficients of potential evapotranspiration index ($E_m$) in the periods 1976–2000 (mm decade$^{-1}$). Additionally, coefficients for central Poland (Łódź) in the period 1951–2000 were enclosed. Trends significant at 0.05 level are in bold.

| Region (station) (see Fig. 1) | Apr | May | Jun | Jul | Aug | Sep | Oct | Sum Apr–Oct |
|---|---|---|---|---|---|---|---|---|
| NW (Szczecin) | **4.4** | 3.5 | 2.3 | 6.9 | **6.6** | 2.8 | 1.6 | **28.0** |
| SW (Wrocław) | **7.1** | 7.4 | 5.4 | 9.0 | **11.2** | 2.7 | −1.0 | **41.6** |
| Central (Łódź) | 2.3 | 3.0 | −2.5 | 4.1 | **6.2** | 1.8 | −0.6 | 14.3 |
| NE (Suwałki) | 2.9 | 4.4 | 1.4 | 8.7 | 5.6 | 2.4 | 0.6 | **25.9** |
| SE (Przemyśl) | 1.6 | 1.8 | 3.6 | 6.5 | 4.1 | −0.1 | −1.1 | 16.4 |
| Central (Łódź) 1951–2000 | 0.5 | **4.9** | −0.2 | 2.2 | **2.6** | −1.4 | 0.1 | 8.8 |

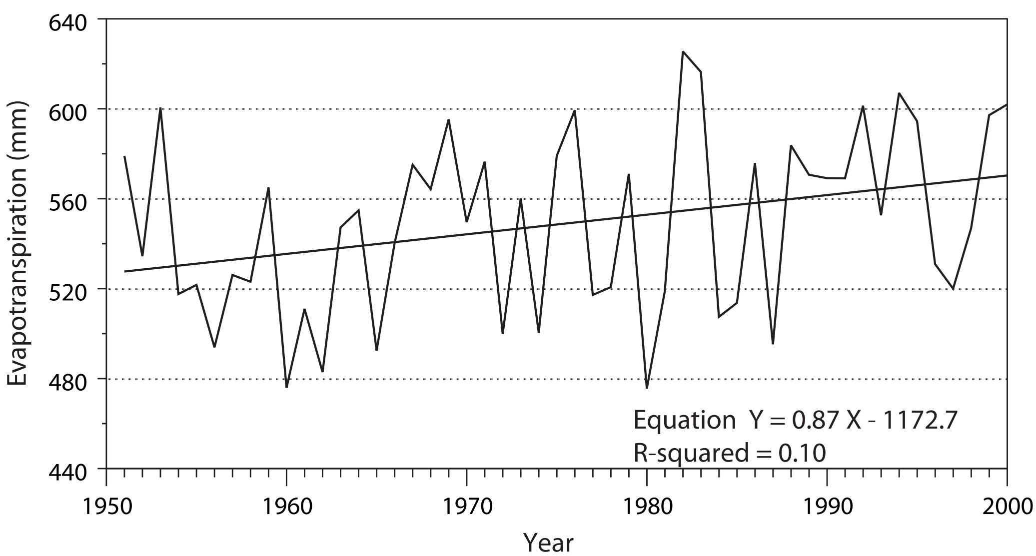


Fig. 3. The course of seasonal (April–October) sums of potential evapotranspiration in central Poland (Łódź) in the period 1951–2000. Linear trend is depicted.

and NW (Szczecin) (Table 13). The trend rate of evapotranspiration in Wrocław exceeds 100 mm in the last 25 years that constitutes 18% of mean seasonal sum. Significant, upward tendency of evapotranspiration was noted in April and August, in western and central Poland. One may state, on the basis of several benchmark stations, that the most distinct rise of evapotranspiration occurred in western and northern part of Poland and the rate of this trend was the highest in May and August. During autumn (September, October) trends of evapotranspiration were slightly negative and statistically insignificant.

Meteorological data obtained from central Poland (Łódź) reveal the significant rise in potential evapotranspiration in May and August during the whole 50-year period (Table 13). The seasonal sum of the evapotranspiration revealed an increase estimated at ca. 44 mm per 50 years (1951–2000), which constitutes 8% of average (549 mm) (Fig. 3). This difference is not statistically significant. However, the number of significant test results (10) with respect to all experiments (48) presented in Table 13 differs from significance level (α). It leads to a conclusion that significant trend coefficients of evapotranspiration may not be the errors of the first kind.

## 4. CONCLUSIONS

The evaluation of climate transformation in Poland, performed in this study, indicates distinct changes of some climatic factors shaping ecosystems functions as for example energy transformation and nutrient cycling. The warming in Poland contributes significantly to the global trend of temperature (Degirmendžić *et al.* 2004, Kundzewicz *et al.* 2004). Intrannual changes of trend coefficients of the air temperature as well as sunshine duration and evapotranspiration are important for the vegetation as the interannual increase of the these parameters.

Several climate indices analysed in this study revealed different directions of changes. The length of the vegetation period, mean temperature in autumn, the frequency of 0°C threshold passage in annual scale as well as annual precipitation sums were relatively stable. Climatic water balance has become more negative but the effect was not significant according to statistical criteria. According to Żmudzka (2002) and Kożuchowski (2004) the second, beside evapotranspiration, component of water balance, i.e. precipitation did not change considerably in annual scale, however significant increase was noted in spring (March).

Distinct changes were detected in case of the following climate indicators:

- Vegetation thermal season – starts earlier, the largest shift of the beginning date was noted in the case of pre-spring season,
- Thermal winter – shortened, episodic cold periods became more frequent (so called "coreless winters"). As a result snow cover duration decreased,
- Temperature in spring – significant rise was observed, the strongest in March,
- The summer season – warmed up. As a consequence the increase of degree days during the vegetation period was observed,
- Sunshine duration – increased in spring and summer,
- Potential evapotranspiration – the rise in warm-half of the year was observed as a result of warming and enhanced sunshine duration in spring-summer season,
- Intrannual precipitation pattern – the increase of spring precipitation was observed alleviating deficit of water in warm season.

On the basis of meteorological data from five selected stations it can be inferred that the most outstanding climate changes occur in the western part of Poland. Climate transformations in this region are characterised by the largest increase in sunshine duration and distinct decrease of the length of thermal winter and the frequency of its occurrence. The increase of the effective temperatures, sunshine duration and evapotranspiration during the vegetation period with gradually milder and shorter winters constitutes undoubtedly the most characteristic picture of the climatic change in Poland at the end of the 20th century.

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