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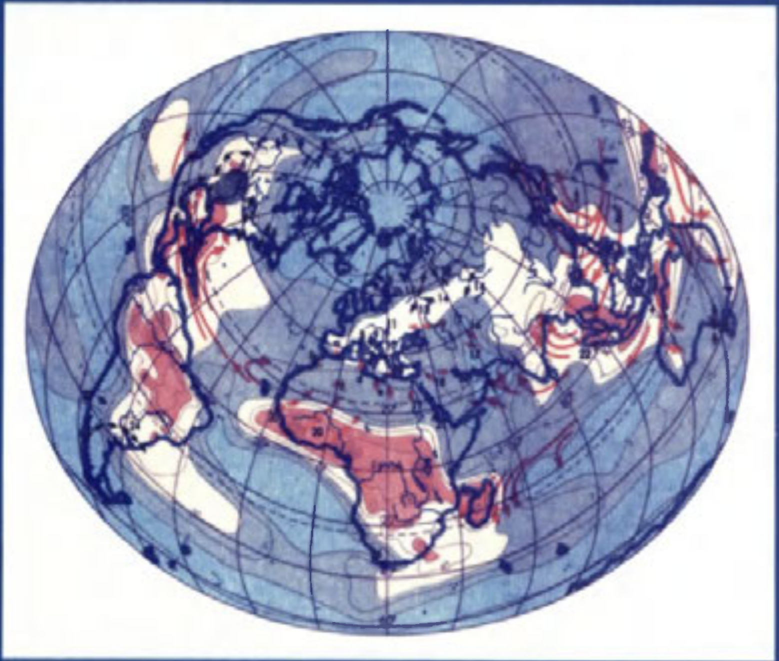
GEOGRAPHIA POLONICA



POLISH ACADEMY OF SCIENCES
INSTITUTE OF GEOGRAPHY AND SPATIAL ORGANIZATION

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PAPERS in GLOBAL CHANGE IGBP, No. 7

Guest Editors:
Krzysztof Kożuchowski and Joanna Wibig
Polish National IGBP Committee

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FOREWORD

In recent years the issue of climate variability has assumed the proportions of an international problem, which is being discussed by politicians, economists and even insurance representatives. Average temperature in the lower troposphere has risen by 0.3–0.6 °C. The existence of global warming is not yet confirmed by this but does seem probable. Similarly it is uncertain whether the changes in the frequency and intensity of some extreme phenomena are determined by natural climate variability or forthcoming global changes. According to the General Circulation Model a rise in air temperature and possibly precipitation is expected, so both natural and anthropogenic ecosystems will suffer the effect of climatic change, as will an agriculture that will have to adjust to future environmental conditions. In order to adapt to the possible changes many countries among them Poland have made efforts with a view to the efficient detection of the proceeding changes, and the prediction and evaluation of scenarios for adaptation. This volume comprises papers presented during the National Conference entitled “Changes and variability of climate and their influence on the economy, ecosystems and human kind”, which was held at the University of Łódź from 4th to 6th November 1999. From among a large number of submitted papers those focusing on the problem of climate variability and prediction and/or adaptation have been chosen.

A survey of 21st century forecasts and reconstructions i.e. testing records of the air temperature, precipitation and wind in Poland in the period 1960–1989 is included in the paper from **M. Liszewska** and **M. Osuch**. Detailed analysis of the results of seven models derived from the Data Distribution Centre in Norwich shows the considerable degree of uncertainty to climate predictions – especially on the basis of control runs.

M. Miętus presents expected changes in air temperature, wind speed, salinity, sea waving and level in the region of the southern Baltic in the case of multiplied CO_2 concentration. Having applied so-called statistical downscaling, the author prepared scenarios for this region according to GCMs. The assessment points to the likelihood of an increase in variability for these parameters, albeit with mean values remaining more or less unchanged.

In the context of the desirable mitigation of the development of the greenhouse effect, **K. Rykowski** analyses the importance of forests in natural carbon cycles. His conclusion may be controversial in the light of traditional views on biosphere protection – he suggests that an effective method of reducing carbon emission into the atmosphere is through its sequestration in the form of wood as well as through the dissemination and prolonged viability of wood products. Also advocated is intensifying tree felling in mature forests up to the permissible extent. The data cited show that soil contains a large amount of carbon.

Most climatological works refer to the history of climate and its temporal dynamics and should therefore be regarded as part of climate monitoring and the documentation of climatic variability. Included in this category are two papers analysing the secular climate record from Śnieżka peak (1605 m. a.s.l., southern Poland). **B. Głowicki** confirms ongoing warming on Śnieżka, which is expressed more distinctly in the minimum temperature record and considerably less so in the maximum temperature record, with the result that there was a decrease in the amplitude of temperature in the 20th century.

Changes in cloudiness in a situation of climate instability appear to be a quite important factor that may regulate the extent of predicted warming. Aside from the assessment of cloudiness the response to temperature changes is ambiguous. In that light the positive trends for cloudiness detected by **M. Dubicka** constitute important information about contemporary climate changes.

K. Kożuchowski and others from the University of Łódź present changes to seasonal variation in pressure, temperature and precipitation proceeding in Poland. While pressure does not reveal any clear-cut annual cycle, the annual courses for other parameters are tending to flatten out. The most distinctive feature of the climatic changes is the decline in the duration of winter and synchronous increase in the duration of transitional seasons of the year. In the case of precipitation, it has been possible to note considerable growth in the half-year harmonic contribution, which is responsible for relatively large winter-autumn falls.

The longest, 300-year, record was that analysed in the paper by **A. Marsz** and **A. Styszyńska** paper. On the basis of long–term data on temperature in Europe it was possible to perform a hypothetical reconstruction of the frequency of maritime-polar air masses modifying thermal conditions in Poland. The course for frequency displays some fluctuation of wide amplitude determining the range of natural climatic variations.

Several following papers concentrate on extreme climatic and hydrological events. **P. Mager**, with colleagues from Institute of Meteorology and Water Management (IMGW) Poznań Branch: **M. Kępińska-Kasprzak**. **R. Farat** and **M. Kuźnicka**, present an overview of the variability to the intensity and frequency of occurrence of atmospheric and hydrological droughts. They show that while before the 1940s, such events appeared regularly and with similar intensities, after the1940s, their occurrence is less regular, despite the lack of an increase in frequency. There are long periods without drought, and then a few following dry years; the intensities of these droughts are also more variable. **Z. Ustrnul** presents an analysis of air temperature extremes. He studied the frequencies of extreme air temperatures for different circulation patterns and has found a close relation. **T. Niedźwiedź** discusses the temporal variability to the appearance of different extreme events and shows that days with very high daily precipitation totals (>50 mm) were more frequent after 1951 than before in the area of southern Poland. No trend was found in the case of temperature extremes, but the range of absolute minimum temperature has increased lately.

The papers presented at the Conference thus survey the changes in the climate and environment observed now·and give some indication of what can happen in the future and what we can do to mitigate the most unfavourable consequences of these changes.

Krzysztof Kożuchowski, Joanna Wibig
Guest Editors

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TRENDS TO CHANGES IN SEASONAL ASPECTS OF THE CLIMATE IN POLAND

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ABSTRACT: The study details the results of a search for changes in the annual rhythms for atmospheric pressure, air temperature and precipitation in Poland in the 19th and 20th centuries. In regard to atmospheric pressure, a reduction in the component amplitude of the annual cycle was noted. Values for annual amplitude of temperature exhibited a downward trend, as did data for the lengths of the seasons with temperatures below zero or in excess of 19°C. In turn, there was an upward trend for the duration of periods with temperatures several degrees above freezing or in the range 14–19°C. The most marked long-term upward trend to temperature was that noted for the five days 11–15 January, which have seen temperatures rise by as much as 4°C in the last decade. Annual courses for precipitation have demonstrated development of the half-year cyclical component responsible for relatively high winter precipitation. Analysis of several time series has allowed for the deducing of decreasing continentality of climate in Poland, a marked warming in the winter-spring period and a general weakening of seasonal contrasts regarding the climate.

KEY WORDS: changes in air temperature and precipitation.

INTRODUCTION

The annual courses for elements of the climate and seasonal differentiation thereof are what determine the "nature" of the climate and to a great extent also the character of its impact upon ecosystems and the economy.

The present study offers an assessment of the trends to the contemporary changes that some seasonal aspects of the Polish climate (i.e. indicators associated with the annual climatic cycle) have been subject to. Specifically, the subjects of analysis have been the annual rhythms to variations in pressure, temperature and precipitation.

The analysis of the courses for atmospheric pressure has involved comparison of series of mean daily values for Warsaw in the years 1821–1880 (as published by Kowalczyk 1882) and 1966–1990. Precipitation has been analysed on the basis of monthly totals for Warsaw in the years 1813–1991, while temperature has been studied using monthly means for Poland's capital in the years 1779–1998 (including within the series published by Lorenc 1994, and taking in the years from 1901). In addition, use has been made of the mean daily temperature figures for Łódź in the years 1931–1998, along with monthly means for several other meteorological stations in Poland. The designation of the thermic seasons of the year made use either of 5-day means or – in the case of series of monthly means – the times at which threshold values for temperature determined by superimposing harmonic components of periods τ_0, ... τ_{12} were exceeded (where τ_0 is a period equal to the length of the series and τ_{12} the annual component).

ATMOSPHERIC PRESSURE

There are various descriptions of the mean annual courses for atmospheric pressure in different periods of the 19th and 20th centuries (e.g. Merecki 1914 for the period 1851–1880; Kosiba 1954 for 1881–1920; Paszyński and Niedźwiedź 1991 for 1931–1960 and Woś 1999 for 1951–1985). These all reveal major changes, especially in regard to the phases of the cyclical components, which a course comprises. An example of the instability to seasonal variations in pressure might be its "highest state" occurring in the 19th century in January (Merecki 1914) and its minimum in December and January of the years 1931–1960, which is visible in the diagram presented by Paszyński and Niedźwiedź (1991).

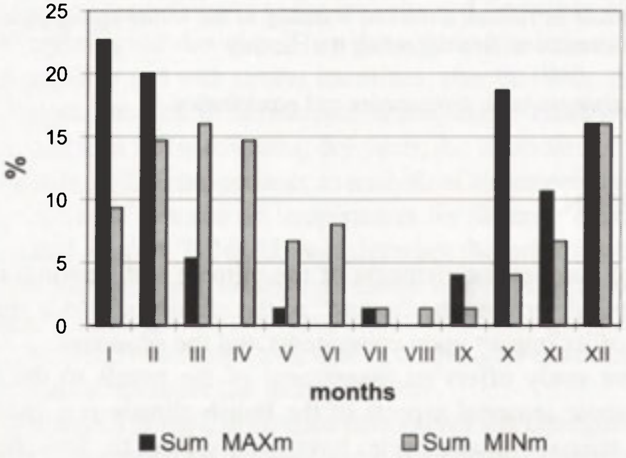

Figure 1. Frequency of occurrence of maxima and minima in the annual cycle for atmospheric pressure in Warsaw 1831–1880, 1966–1990.

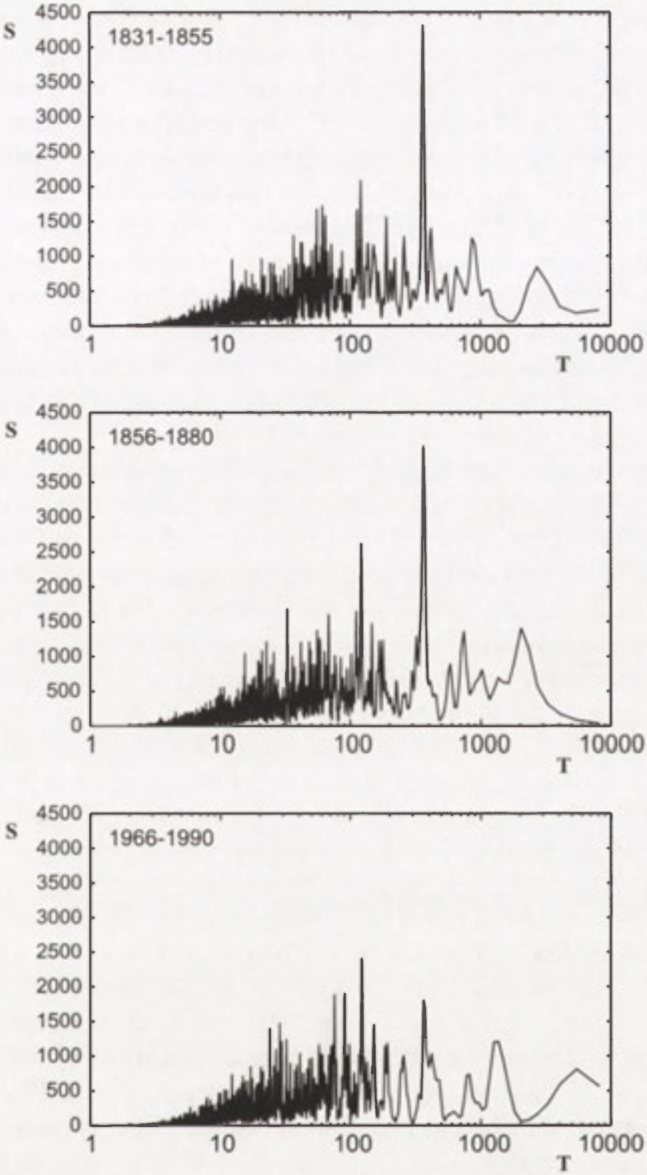

Figure 2. Spectrum to daily values for atmospheric pressure in Warsaw in the periods 1831–1855, 1856–1880 and 1966–1990.

Comparative analysis of mean daily values for pressure in Warsaw in the 19th and 20th centuries (1930–1880 and 1966–1990) reveals that the most striking feature to the annual courses for this element of the climate is the concentration of both the highest and lowest means in the cool half of the year. In different years, the daily maxima appear in the period October–April and the minima between November and March inclusive. The highest and lowest monthly means in turn occur throughout the year with the exception of June and August (Fig. 1).

The averaged courses for pressure in the 19th and 20th centuries possess a certain common rhythm to changes in the course of the year: its most important feature is the lowering of pressure and stabilisation of its fluctuations in spring and summer, as well as a rise with major fluctuations in the autumn–winter season. It is characteristic that the 20th century witnessed a decline by a third in the amplitude to the annual harmonic component of the mean course for pressure. There was however an increase in the half-year and 2- or 4-month components. Corresponding to these changes is the picture for the spectrum of daily means for pressure (Fig. 2). Series from the 19th century have the maximum spectral function, associated with the annual cycle, while this maximum was hardly apparent at all in the series from the years 1966–1990.

Particular manifestations of the disturbances to the annual cycle for pressure are the changes in its phase which allow only for the observation that the cycle maximum is predominantly maintained in the period between October and February. Exceptionally marked variability of the phase to the annual cycle is to be noted in the series for the years 1966–1990. Also visible in this same period is a decline in the amplitude of annual fluctuations, something which recalls the results of harmonic and spectral analysis in attesting to the disappearance of the annual cycle of pressure in the period (Fortuniak et al. 2000).

In contrast, a clear annual cycle to variability in pressure has been sustained, with the mean between-days change in pressure being between 2–3 hPa greater in July and 6–8 hPa greater in the winter months. However, the last 25 years have also witnessed a slight reduction in this variability by c. 0.5 hPa.

AIR TEMPERATURE

The mean annual course for temperature in Poland is reflected to a close degree of approximation by a sinusoid with an amplitude of 21.5°C, a minimum between 17 and 18 January and a maximum between 18 and 19 July (data for Warsaw, Ewert 1979). The phase of the annual harmonic is quite stable, while the amplitude changes markedly, mainly as result of wide variations in minimum temperature. These variations are, *inter alia*, a sign of the formation of fluctuations in the degree of climatic continentality closesly associated with the so-called circulation epochs (Kożuchowski, Trepińska and Wibig 1994; Kożuchowski 1995, 1996; and others). The results are changes in the durations of the thermic seasons of the year, such that declines in the annual amplitude correspond to a curtailment of summer, and especially winter, as well as a prolongation of the transitional seasons of the year.

The durations of the thermic seasons are associated with long-term trends to changes in temperature, as are shown by clear differentiation in different seasons

(Kożuchowski and Marciniak 1994; Lorenc 1994; Cebulak et al. 1996; Trepińska 1997; Boryczka 1998 and others). On the basis of data from 1931 onwards, Olszewski and Żmudzka (1997) pointed to the extension of the growing season, mainly as a result of the bringing-forward of the times at which the 5°C threshold is exceeded.

Various researchers link the cause of these trends with changes in atmospheric circulation, with the overlap of thermic cycles of astrophysical genesis or with the development of urban heat islands, etc. A characteristic feature of these interpretations is the negation of the role of global warming (Lorenc 1994; Boryczka 1998).

Nevertheless, the upward trend for air temperature noticeable in almost all series remains an empirical fact, while the clear difference between summer and winter trends is as noteworthy as the warming itself.

It emerges that the seasonal differentiation to thermal trends in different pentads is more complex than the trends for mean monthly temperatures. The assessment of the trends to changes in mean 5-day air temperatures in Łódź since 1931 (Fig. 3) points to an increase in air temperature in almost all five-day periods from the middle of December through to mid March. The greatest, statistically-significant increase has however been that noted for the period January 11th–15th. Also attaining significance is the warming at the beginning of March, indicative of the development of a pre-spring period (*cf.* Fortuniak et al. 1998). In addition, air temperature increases occur in August and October, and hence in the "late summer" season. Coolings occur in June and July, confirming the observed development of a disturbance to the annual course for air temperature known as the "summer monsoon" (Fortuniak et al. 1998). Downward trends in September and in late November and early December correspond respectively to an enhanced cooling in early autumn and to the early appearance of the first manifestations of winter that have especially been characteristic of recent years. The observed trends reveal ongoing warming in winter and spring, as well as

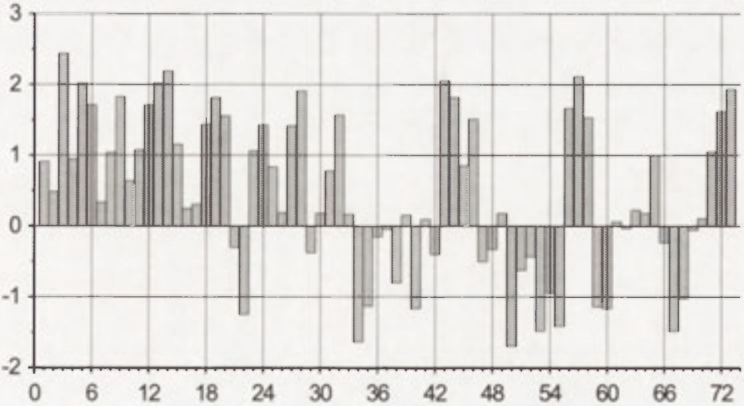

Figure 3. Trends for 5-day means of air temperature in Łodź, 1931–1998. Mann-Kendall ordinate values.

Table 1. Linear trends for the duration of air thermal seasons of the year (days/year).
Bolded coefficients are those significant at $p < 0.05$.

	Zakopane	Gorzow	Suwałki	Wroclaw	Szczecin	Łodz	Kielce	Warszawa
Period	1931–1998	1931–1998	1931–1998	1931–1998	1931–1998	1931–1998	1931–1998	1931–1998
Pre-winter	+0.02 (0.64)	+0.03 (0.46)	**+0.07** (0.00)	+0.08 (0.12)	+0.04 (0.43)	**+0.11** (0.00)	**+0.09** (0.00)	**+0.13** (0.00)
Winter	–0.37 (0.06)	**–0.42** (0.03)	**–0.21** (0.05)	**–0.38** (0.05)	**–0.47** (0.02)	**–0.41** (0.00)	–0.21 (0.06)	**–0.48** (0.00)
Pre-spring	+0.04 (0.34)	+0.04 (0.37)	**+0.07** (0.00)	+0.08 (0.09)	+0.05 (0.38)	**+0.10** (0.00)	**+0.08** (0.00)	**+0.16** (0.00)
Spring	**+0.11** (0.00)	**+0.10** (0.00)	**+0.16** (0.00)	**+0.12** (0.00)	**+0.12** (0.00)	**+0.12** (0.00)	**+0.14** (0.00)	**+0.10** (0.00)
Summer	–0.11 (0.22)	–0.08 (0.33)	**–0.25** (0.01)	–0.14 (0.08)	–0.07 (0.38)	–0.08 (0.28)	**–0.24** (0.00)	–0.03 (0.65)
Autumn	**+0.10** (0.00)	**+0.10** (0.00)	**+0.15** (0.00)	**+0.11** (0.00)	**+0.12** (0.00)	**+0.11** (0.00)	**+0.13** (0.00)	**+0.10** (0.00)

enhancement of the seasonal identity to the course of temperatures in the remaining part of the year. This may be explained by reference to the increasing activity of circulation factors shaping temperature change.

The diversified trends identified for temperature at different times of the year induce particular changes in the duration of the thermal seasons of the year (Tab. 1). The most clearly marked trend here is the significant one for the reduced length of winter which – according to the data – is stronger in the western part of the country. The result is an increasing contrast between the western part of Poland with its short winters, and the eastern part with longer ones. A downward, albeit poorly-defined trend, may also be identified for the length of summer. The lengths of the other seasons of the year have tended to increase in the period since 1931; and in particular there has been a significant and almost even trend for growth in the lengths of autumn and spring, by c. 10 days during the period under study.

The curtailment of winter and corresponding prolongation of the pre-winter period remain the most durable and noteworthy trends to changes in the thermal seasons that are indicated by reference to the Warsaw air temperature series post 1779 (Fig. 4). Irrespective of the doubt that may be expressed regarding the homogeneity of the series, the obtained picture of changes in the duration of these seasons is most probably correct in qualitative terms, at least when it comes to the trends for the present century.

Of greater reliability and uniformity are the series for differences in air temperature between the seasons provided for Warsaw for different years from 1779 onwards. The difference between summer and winter air temperatures, the classic indicator of thermal continentality, shows a non-significant downward trend over the last 220 years (Fig. 5), but the falls in recent times has been below the level observed in the markedly "oceanic" first two decades of the 20th century (Kozuchowski and Marciniak 1991).

Differences in spring and autumn air temperatures have oscillated around a constant level, while a characteristic feature to the changes noted has been a link with differences in summer and winter air temperatures. Thus relatively warm springs have corresponded to small differences in summer and winter temperatures, in line with the rule that a warm winter (i.e. limited summer-winter difference) is followed by a warm spring. The relationship between the two differences considered is particularly well-revealed in the period of milder "oceanic" thermal relations that characterised the early 20th century and the recent period post-1970 (Fig. 5).

Confirmation and further detailing of the emerging picture of seasonal change to the structure of the thermic seasons in the 20th century is offered by analysis of trends for the numbers of days with a mean air temperature in a five-day period whose upper or lower bounds is shifted from tmin to tmax (Fig. 6). Using the air temperature series from the station Warsaw – Astronomic Observatory from the years 1901–1998, it was possible to calculate the trend for the duration

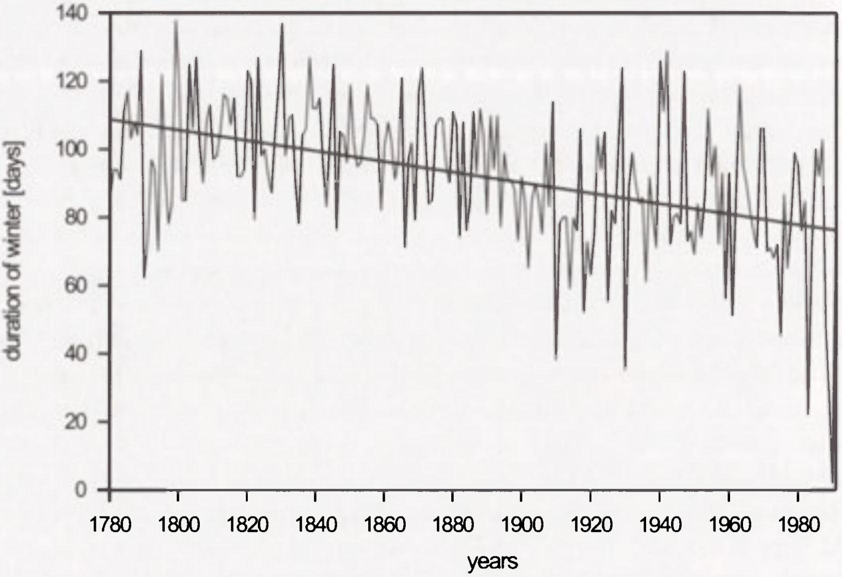

Figure 4. Changes to the length of winter in Warsaw, 1779–1989.

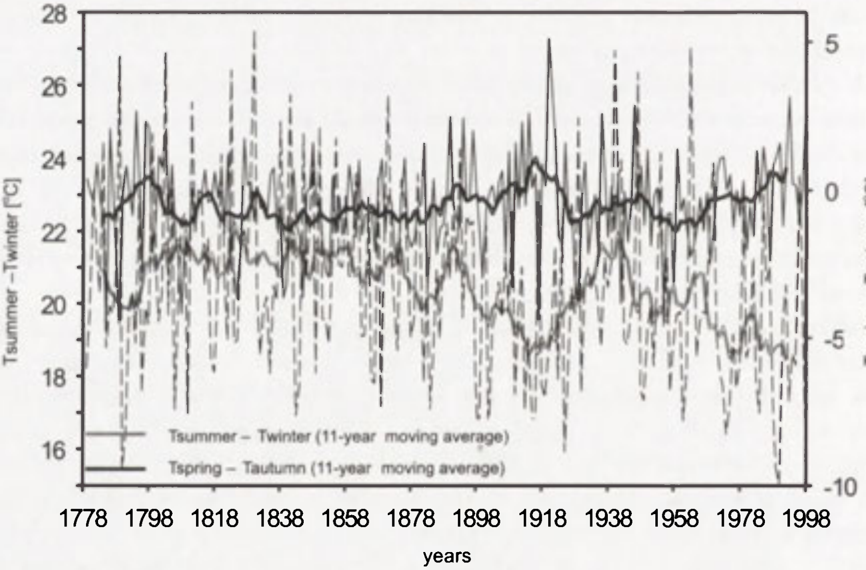

Figure 5. Differences in mean air temperatures of summer and winter and autumn and spring in Warsaw, 1779–1998. Bolded lines show 11-year moving averages.

of periods in a year with air temperatures from –10 to –5, –9 to –4, –8 to –3, etc. It emerged that the length of the seasons with the lowest air temperatures did not change markedly across the analysed period, while there was a significant shortening of the seasons marked by a air temperature range of between –5 and 0ºC. There was also a downward trend for air temperatures in excess of 19ºC. This

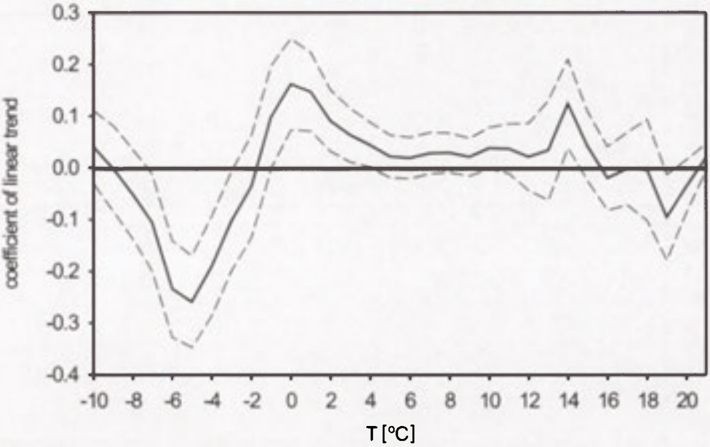

Figure 6. Trends to changes in the length of periods with air temperature (T, T+5) in Warsaw, 1901–1998. The broken lines denote standard error to the coefficient for the trend.

corresponds with the noted regression for the durations of winter and summer. It is obvious that the compensating upward trends were concentrated in neighbouring intervals with temperatures whose frequency of occurrence declined, i.e. in the interval between 0 and 5°C, and 14 and 19°C. The period of the year through which air temperatures within these intervals were maintained increased.

In studying the trends to the duration of the warmer season from a defined thermal threshold, it was noted that the period most prolonged was that with air temperatures above –9°C, while there was also an upward trend for the periods with air temperatures above –8, ... , –6°C. Also prolonged was the period with air temperatures over 0, ... +2°C. The length of the growing season (T > 5°C) has increased at the rate of some 1 day every 10 years, i.e. by almost 10 days since the beginning of the century. According to Olszewski and Żmudzka (1997), this rate increased to 2.1 extra days per 10 years in the period after 1991. In contrast, there has been a decline in the length of the warm season with air temperatures in excess of 17 and 18°C (Fig. 7).

It can be considered as not by chance that the maxima and minima for the coefficient of the trend are associated with defined temperature thresholds – the attention is in particular drawn to the change in the signs of the coefficient for the trend to the duration of periods with temperatures > i < 0°C.

The annual course for air temperature comprises a spring phase of increase and a decline phase in the second half of the year. It is thus possible to speak of trends to the annual course, as well as of summer and winter culminations (turning-points) corresponding to the change in the sign for these trends. The times so defined may serve in the division of the year into two parts of “rising” and “falling” air temperatures prior to and following the summer turning point. The quotient of the duration times of these parts may be regarded as an indicator of the asymmetry to the annual course of air temperature (Ewert 1979). The time

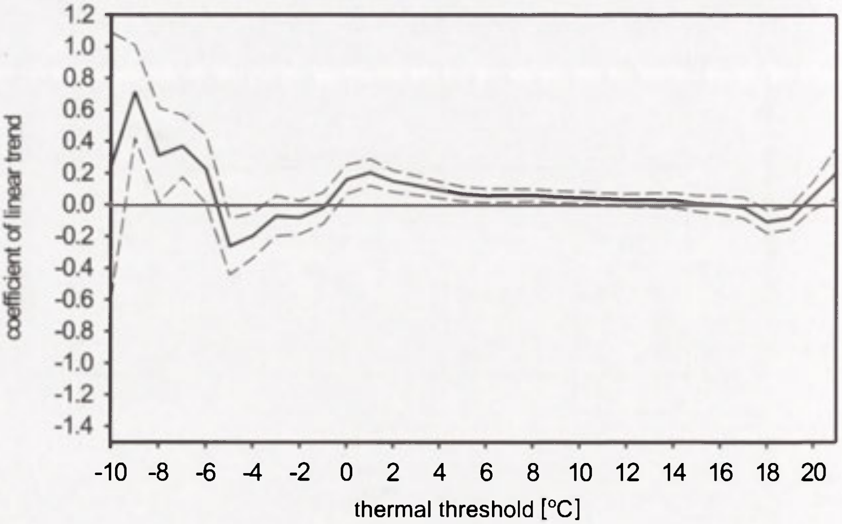

Figure 7. Trends to changes in the length of the season with a air temperature higher than a given thermic threshold in Warsaw, 1901–1998. Broken line ± standard error for coefficient.

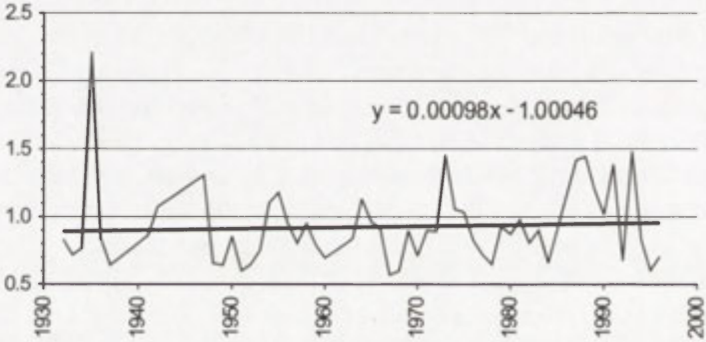

Figure 8. Ratio of length of period with falling air temperature to length of period with rising temperature through the year, Łodz, 1931–1998.

Table 2. Mean lengths of seasons of the year in Warsaw in selected decades (days).

Period	Winter	Pre-spring period	Spring	Summer	Autumn	Pre-winter period
1910–1919	75.4	34.0	60.2	101.1	59.7	35.2
1930–1939	79.9	31.7	55.1	109.9	53.7	30.2
1989–1998	61.5	37.4	59.0	111.1	58.1	36.2

of the change in the direction of the trend has been designated using a sequential version of the Mann-Kendall test (Gerstengarbe and Werner 1999).

The rising phase to the annual course is rather longer than the decline phase. The years 1931–1998 were characterised, not only by considerable fluctuations

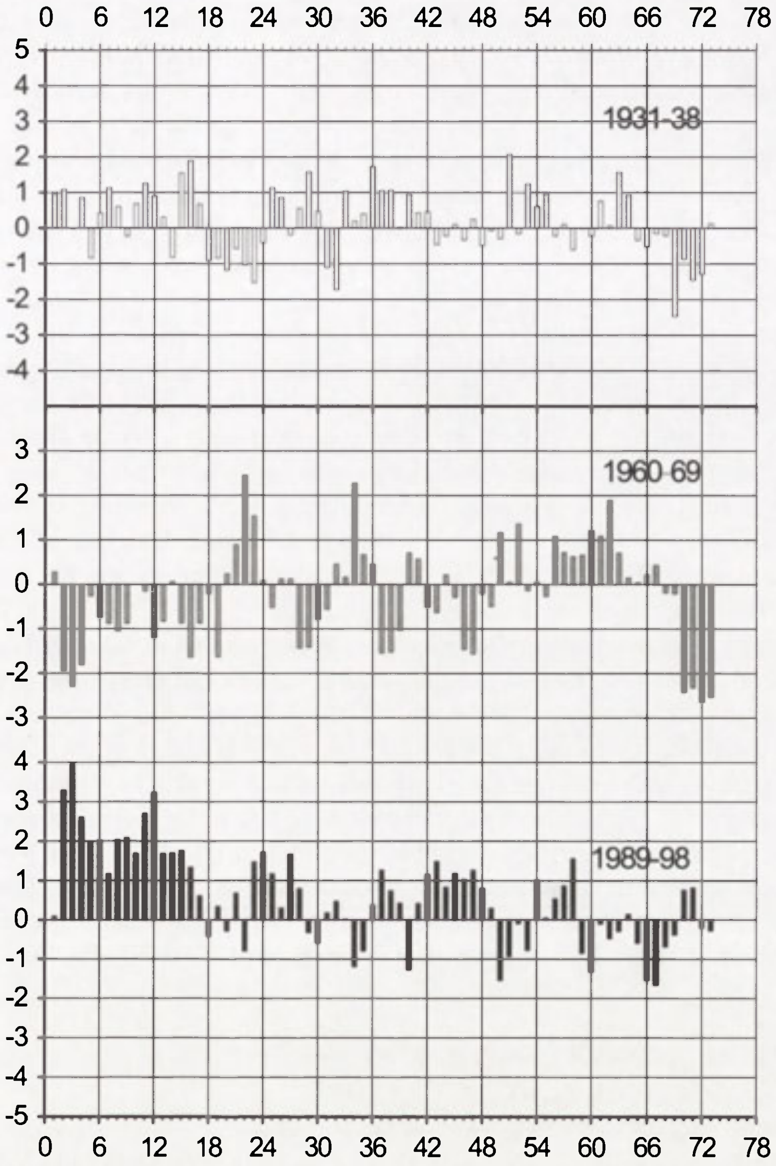

Figure 9. Departures from the means for the years 1931–1998 noted for 5-day means of air temperature in Łódź in the years 1931–1938, 1960–1969 and 1989–1998.

to changes in these two parts of the year, but also by a certain lengthening of the season of air temperature decline (Fig. 8). This trend has mainly been shaped by the earlier times of onset of the summer "turning points" for air temperature.

In the 1990s, Poland experienced a noticeable warming, and one with a certain uniqueness in that – against the background of earlier trends – there were a series of relatively warm summer seasons.

Accepting intervals for temperature corresponding to thresholds for which the probability of exceedance is 90, 75, 25 and 10%, and establishing corresponding classes of very cold, cold, warm and very warm months, it was possible to study the frequency of occurrence of the different classes on the basis of data for the station Warsaw – Astronomic Observatory (1901–1998). In the 1990s, more than 34% of months were in the warm and very warm categories while less than 19% were cold or very cold. It is characteristic that the greater part of the monthly averages for July and August, as well as for January, were among those in the warm and very warm categories.

The mean air temperature in Warsaw in the decade 1989–1998 was of +8.9°C and was higher than both the means for the warm decade of the 1930s and for the warm "oceanic" decade beginning in 1910. Comparisons of the lengths of the thermic seasons of the year in Warsaw in the three selected decades are as set out in Table 2. What is clear above all is the considerable curtailment of winter in the last decade.

The majority of the seasonal differentiation to the warming in the years 1989–1998 may be traced on Figure 9, which shows the departure of the mean 5-day air temperatures in Łódź in this period from the means for the years 1931–1998. The departure for January 11th–15th attains 4°C! (Fig. 3). Positive departures also take in January and February before ending in the five-day period March 21st–25th. The other part of the year also has a clear prevalence of positive departures for air temperature in the years 1989–1998, including in summer.

The thermal anomalies for the period 1989–1998 make clear the scale of the recent warming and would, it seems, allow for the assigning to it of the description "exceptional", especially against the background of the anomalies associated with the previously-observed fluctuations of air temperature. For both the departures of the warm years of the 1930s and those in the known cooling phase of the 1960s failed to manifest such great dimensions, and nor did they appear as systematically through the year as did the winter warming in the decade 1989–1998 (Fig. 9).

THE CIRCULATORY CONDITIONING OF THE COURSE OF AIR TEMPERATURE

Atmospheric circulation is a major factor shaping both short- and long-term fluctuations to air temperature in Poland, as has been documented in many studies (Kożuchowski and Marciniak 1991, 1994; Lorenc 1994; Trepińska 1997; Ustrnul 1997; Wibig 1993). The present study has made an assessment of the link between mean monthly air temperature in Warsaw in the period 1901–1970 and the circulation conditions as defined by the index of the North Atlantic Oscillation (NAO) (Jones et al. 1997) and by the frequency of occurrence of anticylonic pressure systems over Poland as referred to in the Osuchowska-Klein classification (1978, 1991). Account was taken of atmospheric circulation types C2D, D2C, G, E2C, E and E1.

Table 3. Equations for the multiple regression of air temperature (T_{est}) in Warsaw (1901–1970) against the NAO index and frequency of anticyclonal (AC) types after Osuchowskiej-Klein. Bolded values of P denote a dependent relationship significant at $p < 0.05$.

M	Multiple regression equation	P	$R_{T.\,NAO,\,AC}$	$R_{TNAO,\,AC}$	$R_{TAO,\,NAO}$
I	$T_{est} = 1.008 \times NAO - 0.209 \times AC - 1.289$	**0.0000**	0.685	0.598	–0.510
II	$T_{est} = 0.845 \times NAO - 0.147 \times AC - 1.107$	**0.0000**	0.650	0.544	–0.312
III	$T_{est} = 0.852 \times NAO - 0.019 \times AC + 1.959$	**0.0000**	0.605	0.604	–0.067
IV	$T_{est} = 0.244 \times NAO + 0.031 \times AC + 7.521$	0.1400	0.239	0.212	0.085
V	$T_{est} = 0.016 \times NAO + 0.077 \times AC + 12.824$	0.1104	0.252	0.013	0.250
VI	$T_{est} = -0.071 \times NAO + 0.083 \times AC + 16.149$	**0.0276**	0.319	–0.067	0.318
VII	$T_{est} = 0.012 \times NAO + 0.075 \times AC + 17.879$	**0.0000**	0.393	0.012	0.363
VIII	$T_{est} = -0.219 \times NAO + 0.086 \times AC + 16.870$	**0.0002**	0.473	–0.266	0.447
IX	$T_{est} = 0.370 \times NAO + 0.018 \times AC + 13.577$	**0.0045**	0.386	0.378	0.077
X	$T_{est} = 0.411 \times NAO - 0.057 \times AC + 9.185$	**0.0005**	0.452	0.377	–0.272
XI	$T_{est} = 0.409 \times NAO - 0.123 \times AC + 4.271$	**0.0001**	0.497	0.328	–0.425
XII	$T_{est} = 0.349 \times NAO - 0.184 \times AC + 0.861$	**0.0000**	0.587	0.280	–0.532

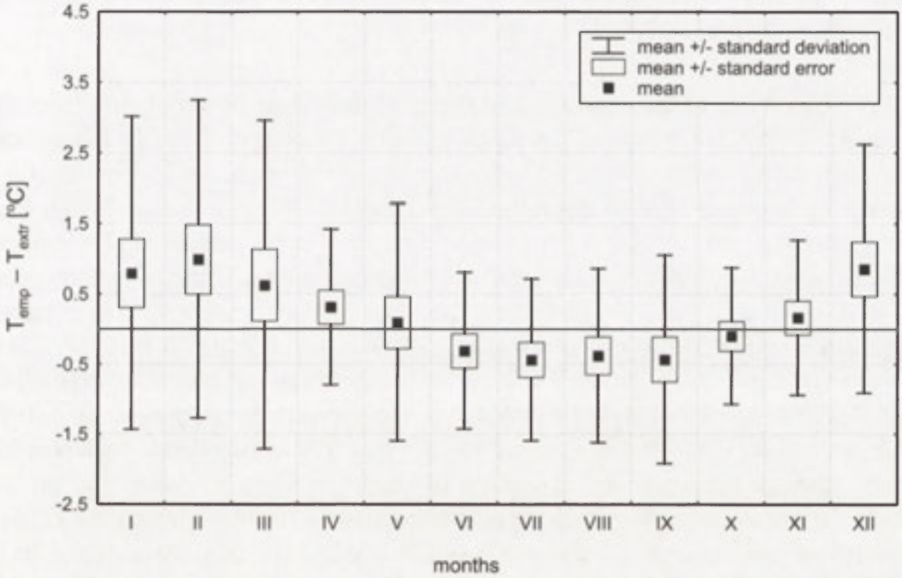

Figure 10. Differences between mean monthly air temperature observed in Warsaw in the years 1971–1990 and means calculated from regression equations for T_{est}.

The multiple regression equations T(NAO, AC) are presented in Table 3, as are the multiple and partial correlation coefficients. In line with expectations, the strongest influence of circulation is that upon temperatures in the winter months, with high values for the coefficient of NAO zonal circulation exerting an impact by raising the temperature in the cool season of the year and (more weakly) by lowering temperature in summer (July and August). In turn, the frequency of anticyclones is correlated with summer air temperature and inversely correlated with that in winter.

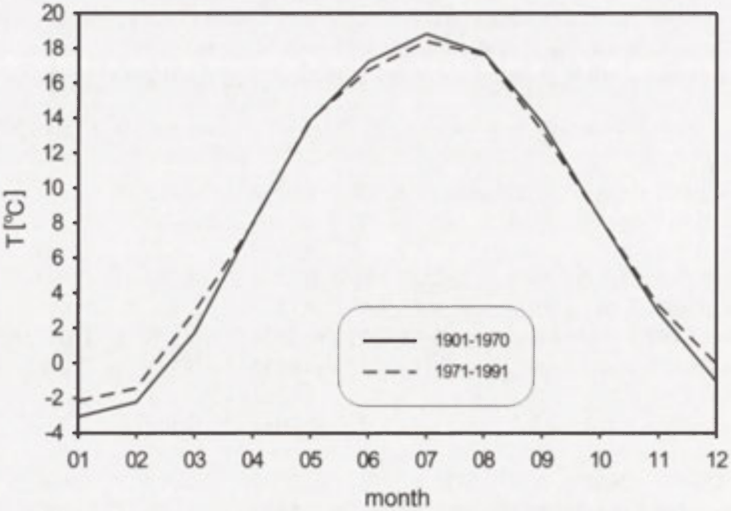

Figure 11. Air temperature (T_{est}) in Warsaw, monthly means for 1901–1970 and 1971–1991.

Use was made of the equation and series of indicators of circulation from the years 1971–1991 to estimate the mean monthly air temperatures in the period. Estimate values were compared with the empirical ones, as in Figure 10. It emerged that observed air temperatures for the years 1971–1991 were higher than those estimated on the basis of regression equations in the case of the December–March period, and lower than or equal to the estimated ones in the rest of the year.

It is obviously possible to ignore the seasonal differences to the obtained departures, considering them to be statistically non-significant. Nevertheless, it is worth pointing to the notable degree of accord between the course of departures T_{emp}-T_{est} and changes in the mean monthly air temperature in the period 1971–1991 (Fig. 11), as well as – more generally – to stress the concordance between this course and the seasonal differentiation to observed thermal trends, i.e. the increase in temperature in winter and the tendency for summer to be cooler. Conclusions explaining this effect should be looked for in studies of the links between air temperature and other factors that shape its course, notably other indicators of circulation. It may be that the emergence of the departures (T_{emp}-T_{est}) under discussion was favoured by activation of the so-called secondary types of circulation shaping the southerly direction of the air flow in Poland (D2C, G, F and BE). The frequency of the latter has increased greatly – even doubled – in the last 20 years (Lorenc 1994). The above analysis may only allow it be stated that the warming observed after 1971, as well as the downward trend for air temperature in summer, cannot be explained by reference to changes in the intensity of zonal circulation or the frequency of occurrence of anticyclones.

PRECIPITATION

Precipitation in Central Poland is representative of the continental-maritime type of annual course, with a maximum in July and a prevalence of autumn over spring precipitation (Chomicz 1971). The "maritime" features of the precipitation regime were noted as early as in 1914, by Merecki, who pointed to a secondary precipitation maximum affecting Warsaw in December. The degree of pluvial continentality in Poland showed an upward trend in the 20th century, but this was already slowing down by the 1970s, with some indicators of precipitation beginning to reflect a renewed oceanicity to the regime (Kozuchowski and Wibig 1988). These fluctuations developed against the background of a steady development of the "maritime" component to the seasonal distribution of precipitation, i.e. the half-year cycle responsible for the relatively high level of winter precipitation. The development of the half-year harmonic of the precipitation cycle is confirmed by the results of analysis of monthly series for precipitation totals in Warsaw post 1813.

Ewert (1984) presented differences in the second harmonic to the course of precipitation in Poland on the basis of data from the period 1891–1930. In the case of the Central Poland area, this component explains c. 15% of the variance to the annual course of precipitation and, according to this author, is a reflection of annual changes in the influence of zonal circulation in Poland.

The spectrum of monthly variation to precipitation totals in Warsaw (1813–1991) is dominated by two periodicities: a marked peak of annual variations and a rather more weakly-marked maximum of spectrum strength corresponding to the half-yearly cycle. The search for long-term trends to the changes in both components made use of the following procedure: matched to data from the five first years of the studied series were Fourier parameters of a sinusoid with 6- and 12-month periodicities. Next, with the five-year period having been advanced by one month, the next amplitudes and phases were counted – up to the last section of the time series. The results are presented in Figure 12. It is possible to observe a downward trend for the amplitude of the 12-month cycle and an upward trend for that of the half-yearly cycle. The values for the trends are as presented in Table 4. On the basis of Mann-Kendall and Spearman tests it is possible to state that the two trends are significant at a confidence level of 99.9%. The phase of the annual cycle does not undergo change, while the phase of the 6-month cycle changes in such a way that maxima occur ever earlier. Although this trend attains

Table 4. Amplitudes (A) and linear-trend coefficients for changes in amplitude (B) in relation to two cyclical components to precipitation in Warsaw (1813–1991).

Component	12-month cycle	6-month cycle
A	22.89±0.25 [mm]	8.52+0.19 [mm]
B	B(–1.8±0.2) $\cdot 10^{-3}$ [mm/month]	(1.5±0.2) $\cdot 10^{-3}$ [mm/month]

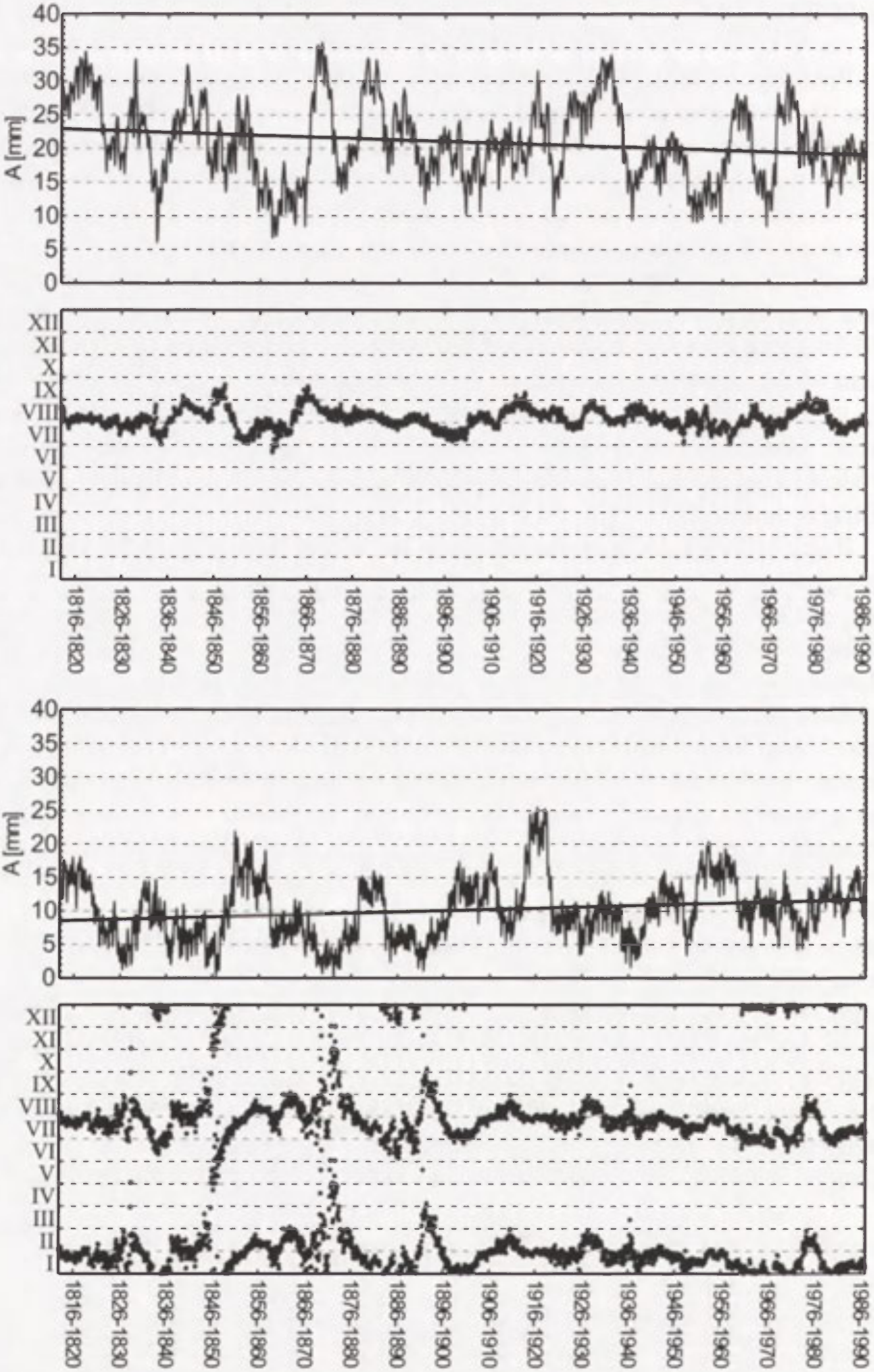

Figure 12. Amplitude (A) and phase (time of maximum) for harmonics I (upper figure) and II (lower figure) to the annual course of precipitation in Warsaw (1813–1991).

statistical significance, its physical significance is tiny, since it denotes a shift in extremes of only one day in the course of 200 years.

The obtained trends for components of the annual course of precipitation are associated with considerable quasicyclical fluctuations (Fig. 12). In the case of changes in the phase of the half-yearly component, it is possible to note a certain stabilisation to times of the occurrence of extremes over the century. In connection with the increasing amplitude of the half-yearly harmonic, this may attest to the increasing significance of this component in shaping the levels and seasonality to the breakdown of precipitation across the year, in other words to progressively increasing oceanicity of climate. Also speaking for this is the declining amplitude of annual variations in temperature and the prolongation of transitional seasons of the year.

In adding a conclusion as to the disappearance of the annual cycle of changes in pressure, it may be considered that several of the features to the course of climatic elements analysed here attest to a weakening of seasonal climatic contrasts. A leading role in these changes is undoubtedly played by the winter-spring warming, whose dimensions in the last decade have gone beyond the variability of the climate observed in Poland over at least the last hundred years.

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THE DYNAMICS TO SELECTED EXTREME CLIMATIC EVENTS IN POLAND

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ABSTRACT: The article presents the variability to selected extreme climatic phenomena in Poland in the second half of the 20th century. The main attention is paid to the search for exceptional values for indicators or trends that might be regarded as effects of global warming. Among the circulation indicators considered are the variability to the influx of Arctic and tropical air masses in the period 1951–1999, as well as the numbers of days with fronts. In turn, elaborated for the period 1966–1999 was the variability in absolute maxima and minima for pressure, as well as extreme values for pressure tendency, and the occurrence of very strong winds. The greatest changes were found to have occurred in the case of extremes of temperature: from 1982 onwards in the case of absolute maxima and from 1973 on in the case of absolute minima and amplitudes of temperature. These generally attest to an increase in the oceanicity of the Polish climate. In the case of extreme precipitation events, a transition to a rather wetter phase of climate has been noted since 1995. However, there is no sign of any departure for any of the elements studied that has exceeded the values typical for fluctuations of climate in the 20th century, and could therefore be taken as indicating a permanent change in the climate.

KEY WORDS: climatic change, extreme climatic events, Poland.

INTRODUCTION

The issue of extreme climatic phenomena is among the leading ones for those researching the world's climate. It arouses great interest among both such scientific organisations as the WMO, and among the governments and economic institutions of different countries. Most difficult to explain are the causes of climate change, while attempts to predict further changes are also a source of controversy. Many of the changes in question are global in character and may turn out to be of great significance for humankind (Obrębska-Starkel and Starkel 1991; Trepińska et al. 1997; Starkel 1999).

The undertaking of this research is even further justified by the fact that many extremes of climate have been noted in recent years (Cebulak and Limanówka 1997; Cebulak and Niedźwiedź 1997), including changes to the trends for winter temperatures. After the exceptional positive anomalies occurring in the winters between 1989 and 1994 in Poland (and most especially the warm January of 1994), there was the longlasting winter of 1995/96 and the relatively cool one of 1996/97 (Kraków's December of 1996 was the second coldest in the years 1951–1996 inclusive, after that of 1969). Winter 1997/98 was in turn mild. The last decade has also witnessed extreme thermal events in summer (with summer 1992 seeing the greatest thermic anomalies noted in Kraków for 200 years, and July 1994 also proving exceptional). A great positive anomaly to temperature was also to be noted in April 2000 – the warmest in 200 years. The ongoing warming has been associated with perceptible shortages of rain, while the summers of 1992 and 1994 were characterised by catastrophic drought over much of the country. There is a need for detailed recognition of both the scale and scope of such anomalies, and their causes. Since 1995 there has been a steady and noticeable rise in summer precipitation, and even states of excessive rainfall as in the very wet July of 1996 that affected Wielkopolska, and led to flooding in the Carpathians in September. Of course, there has been nothing to compare with the severity of the economic losses and cost in lives (55) associated with the catastrophic July 1997 floods in the south of Poland (the subject of a separate work – Niedźwiedź 1999). Local extreme phenomena have also been marked, with examples being recent extreme storm rainfall events over the Małopolska Upland: near Miechów in September 1995, twice in May 1996 at Sułoszowa in the Prądnik basin, in Kłodzko in July 1998 and at Pałecznica near Proszowice in April 2000. In turn, considerable losses were incurred in the Podkarpacie region in summer 1999 as a result of a large number of local events of an extreme nature (storms, downpours, hail and strong winds).

It is suspected that one of the factors influencing contemporary climatic conditions is human economic activity through the supply to the atmosphere of huge amounts of particulate and gaseous pollutants, including the additional heat and carbon dioxide released by the burning of various substances. All of these processes induce the so-called greenhouse effect favouring a considerable rise in temperature. A working hypothesis that has been advanced holds that the effect will make itself felt in a considerable increase in the frequency of occurrence of extreme events (Starkel 1999; Wigley 1988). It is for this reason that one of the aims of the present study has been to determine the dynamics of selected extremes of climate over the longer term.

MATERIALS AND METHODS

The greater part of the material was collected within the framework of research topic M-2 coordinated by the author and entitled "Extreme climatic phenomena in Poland – spatial structure, dynamics and threats". This has been implemented over the last several years within the Kraków branch of the Institute of Meteorology and Water Management, with account having been taken of the period 1951–1998. In turn, work continued at the Department of Climatology of the University of Silesia in relation to the variability of occurrence of selected extreme climatic phenomena over long periods, with use being made of world climatic bases, including the Global Historical Climate Network made available over the Internet by the NOAA.

Past research on the climate, its variations and long-term changes has largely been confined to the elements of air temperature and atmospheric precipitation. However, the climate is a complex of mutually-interlinked meteorological elements, with research confined to the aforementioned elements being very far from satisfactory when it comnes to an assessment of the climate on every scale. Studies of the causes of change should be sought in the variability to atmospheric circulation, so research on extreme phenomena was linked with the dynamic to extreme circulation phenomena (Ustrnul 1997a, b), with account also being taken of the frequency of occurrence of the masses of Arctic and tropical air generating extreme thermic situations. The variability to indicators of western and southern circulation and cyclonicity was elaborated for the years 1873–1999, with attention being paid to the appearance of extreme values. The occurrence of masses of air and arrival of atmospheric fronts was also presented for the period 1951–1999. These changes are the result of the high dynamic to pressure systems which has been presented in the courses for extremes of atmospheric pressure and the frequency of exceptionally large values for barometric tendency exceeding ±5.0 hPa in the course of a 3-hour period. A supplement to this part of the work has taken the form of a characterisation of very strong winds (stronger than 15 ms^{-1}).

From among the extreme thermic phenomena, the study focused upon the variability of long-term absolute maxima and minima of temperature, as well as absolute values for annual amplitude.

Given in the case of atmospheric precipitation – apart from the extreme daily and annual values – were Polish lowland averages (14 best stations) for the characterisation of daily falls exceeding 20 mm, as well as days without precipitation.

THE ADVECTION OF ARCTIC AND TROPICAL AIR MASSES

Among the extreme circulation characteristics of the climate, advection of Arctic air over Poland has been the subject of a clear upward trend in recent years (Fig. 1), increasing by c. 35 days in the course of 49 years. In an average year, such a cool air mass extended over Poland for 29 days, however in the years 1976–1979 there were 56–60 such days a year, while in 1997 there were 53. It was in this latter year that an increase in the activity of meridional circulation led to the exceptionally high rainfalls noted in southern Poland in July.

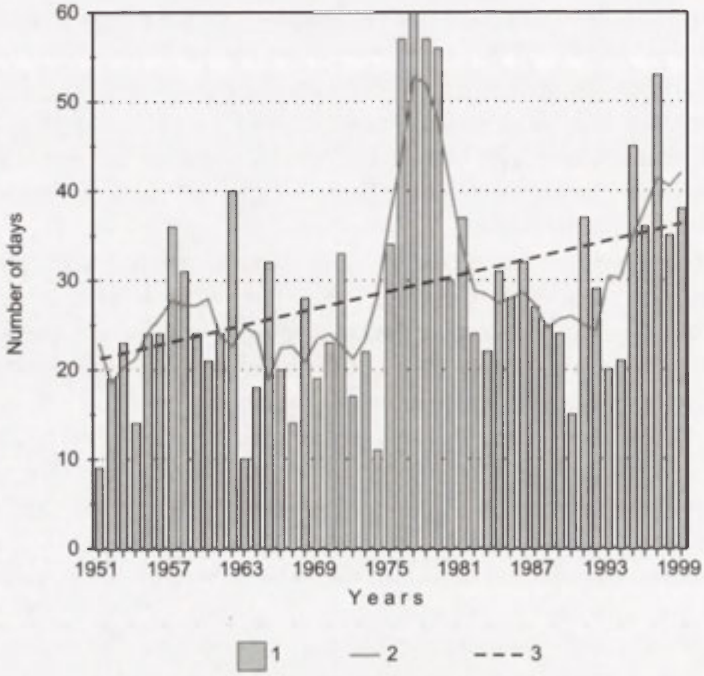

Figure 1. Long-term variability to the frequency of Arctic air-mass advection (1951–1999). 1 – annual number of days, 2 – moving averages (5-year), 3 – linear trend.

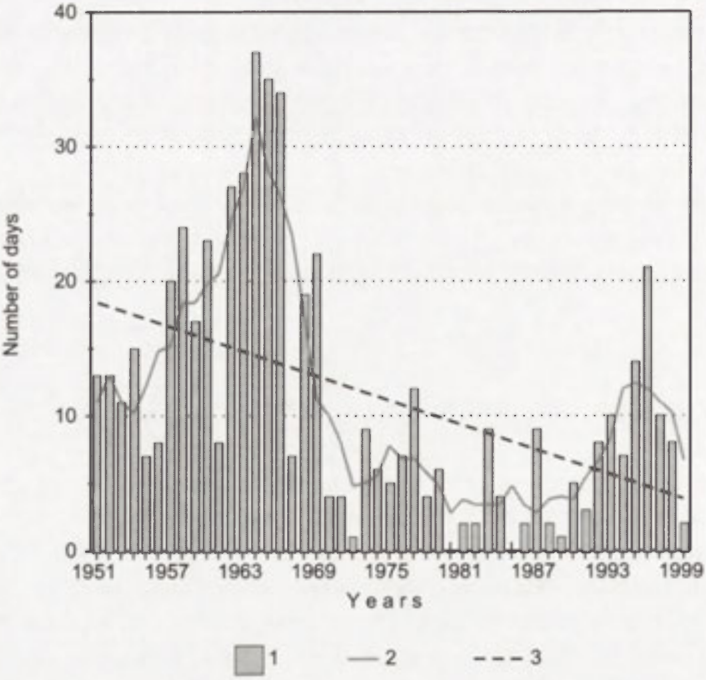

Figure 2. Long-term variability to the frequency of tropical air-mass advection (1951–1999). 1 – annual number of days, 2 – moving averages (5-year), 3 – linear trend.

Maxima for the advection of Arctic air are to be noted through the course of the year, being responsible for the so-called “return of winter” and severe ground frosts as late as April and May, as well as for cold periods in September and October. Overall, Arctic air was observed least often in the years 1951 (9 days), 1963 (10), 1974 (11) and 1990 (15).

Tropical air has in turn shown a marked downward trend for frequency of occurrence – from 18 days a year in the period 1951–1955 to 5 days in the years 1995–1999 (Fig. 2), as compared with the mean figure for the whole period of 11 days per year. It is easy to identify a period of enhanced advection in the years 1951–1969, with a maximum in the period 1962–1966 (with as many as 37 days in 1964). Later, in the period 1970–1994, such tropical air occurred more rarely, to the point where it was not even noted at all in 1980 and 1985. Renewed influxes have however been noted most recently, with 14 days of tropical air in 1995 and 21 in 1996. Interestingly, the years 1970–1994 are characterised not only by the limited frequency of advection of tropical air, but also by the rarity of advections of Arctic air, while the period from 1995 onwards has seen a renewed rise in the frequency of incursion of both of these thermally-extreme kinds of air mass.

THE FREQUENCY OF OCCURRENCE OF ATMOSPHERIC FRONTS

As many extreme climatic phenomena (like storms, very strong winds, etc.) are generated by fronts, their frequency of arrival over Poland is also worth researching (Fig. 3). On average, such fronts are present for around 150 days

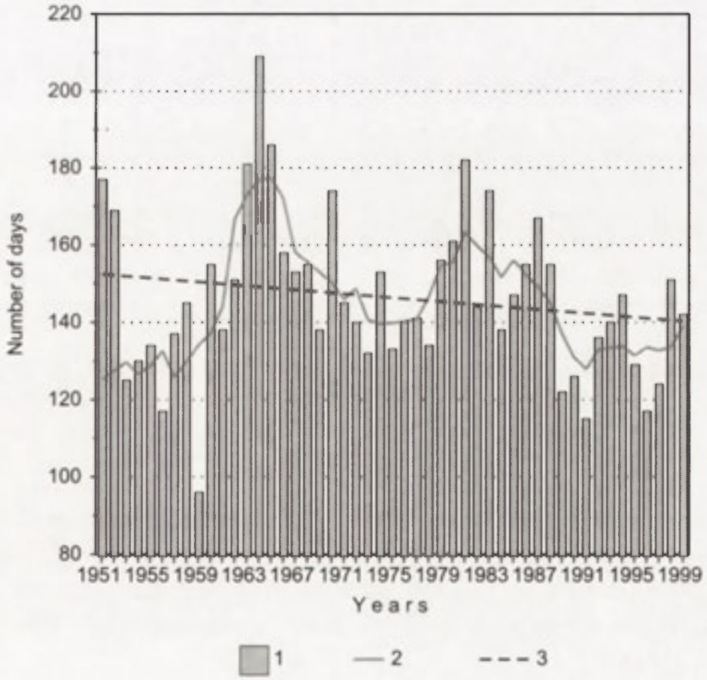

Figure 3. Long-term variability to the frequency of fronts passing over Poland (1951–1999). 1 – annual number of days, 2 – moving averages (5-year), 3 – linear trend.

a year, with the recent trend for their occurrence being downward, albeit with statistical significance not achieved. The last 50 years have included three identifiable periods with a greater number of fronts, i.e. 1951–1952, 1960–1970 (with the peak of 210 days in 1963) and 1979–1988. The most limited occurrence of fronts came in 1959, when they were present over the country for only 97 days.

EXTREME VALUES FOR ATMOSPHERIC PRESSURE

The indicators of atmospheric circulation are often associated with extremes of pressure, as is seen for Warsaw in the years 1966–1999 (Fig. 4). There has been a marked upward trend for absolute pressure maxima, from 1041 to 1046 hPa, while the highest values of all – adjusted to sea level – were of 1050 hPa in 1992 and 1997. However, it was only in 1978 that the highest pressure noted in the year did not exceed 1036 hPa.

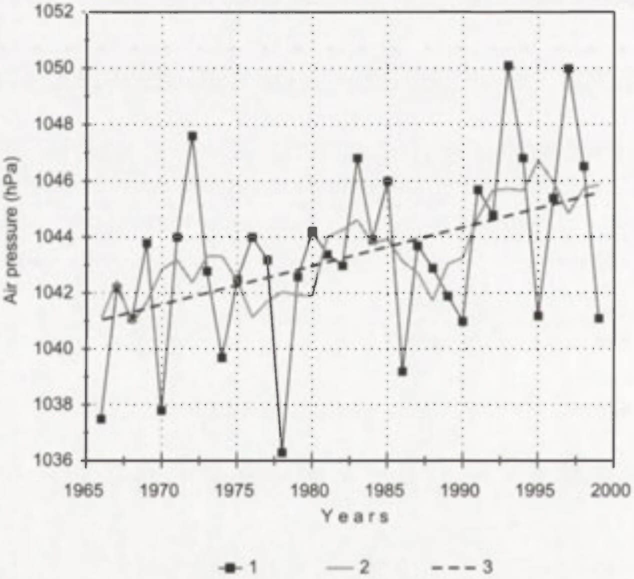

Figure 4. Long-term variability to the absolute maximum of sea-level air pressure in Warsaw (1966–1999).

1 – annual absolute maximum, 2 – moving averages (5-year), 3 – linear trend.

Absolute minima for pressure (Fig. 5) have been characterised by greater fluctuation than the maxima, but with no clear trend to be noted. The pressure fell below 975 hPa as many as four times in the study period, with the lowest figure being the 971 hPa noted in 1989. Falls in pressure below 990 hPa are an almost annual event.

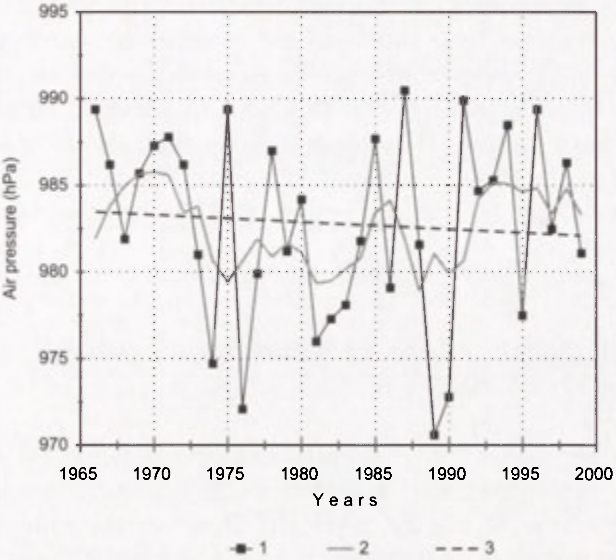

Figure 5. Long-term variability to the absolute minimum of sea-level air pressure in Warsaw (1966–1999).

1 – annual absolute minimum, 2 – moving averages (5-year), 3 – linear trend.

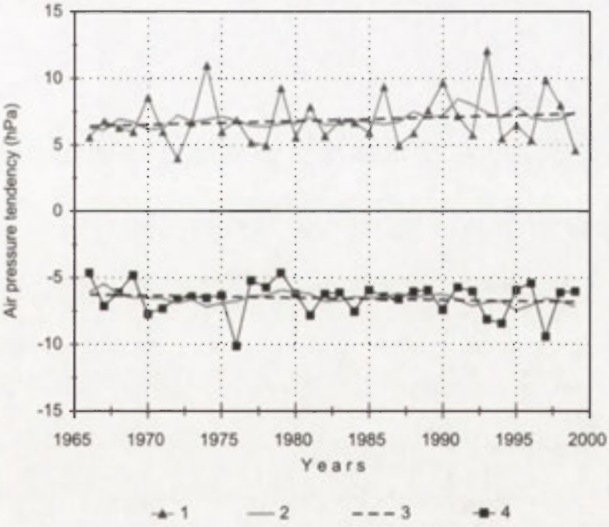

Figure 6. Long-term variability to the extreme values for air pressure tendency (hPa/3h) in Warsaw (1966–1999).

1 – greatest increase in pressure, 2 – moving averages (5-year), 3 – linear trend, 4 – smallest decrease in pressure.

From among the different pressure characteristics, the greatest attention has been paid to the brief but large variations in pressure over 3-hour periods (Falarz 1997) that are noted at meteorological stations as barometric tendencies. In Warsaw, the extreme values for such variations may exceed 10 hPa in 3 hours roughly twice every 50 years (Fig. 6). In turn, three-hour rises or falls in excess of 5.0 hPa are an almost annual event. Analysis of the trends suggests that the last 50 years have witnessed a small increase in the range of variation to such barometric tendencies.

THE VARIABILITY TO THE OCCURRENCE OF VERY STRONG WINDS

Winds stronger than 15 ms^{-1} over 10 minutes do not occur very often in Poland away from the coast and the mountains. In Warsaw, there are on average only 2.5 days a year with such winds (Fig. 7). However, the number does fluctuate markedly from year to year, between the 0 noted in 1977 and 1989 and the 7 days with such winds in 1992. Nevertheless, the fluctuations have been rather irregular and do not conform to any particular trend.

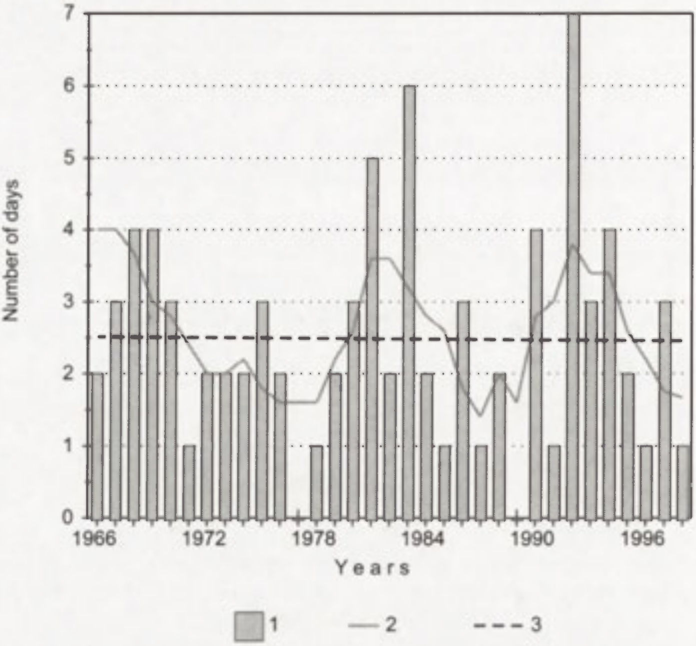

Figure 7. Long-term variability to the occurrence of gales (>15 m/s) in Warsaw (1966–1998).

1 – annual number of days, 2 – moving averages (5-year), 3 – linear trend.

EXTREME VALUES FOR AIR TEMPERATURE

Three weather stations were chosen to present the fluctuation and variability to long-term absolute extremes of air temperature. These are Suwałki, as representative of the coolest part of Poland; Słubice – the warmest, and Warsaw, representing the centre of the country. The highest maximum air temperature noted to date in Poland is taken to be the 40.2°C recorded in Prószków near Opole on July 29th 1921 (Paszyński and Niedźwiedź 1999). D. Kuziemska (1983) in turn quotes a value of 38.9°C noted on August 19th 1892 in Legnica and Zielona Góra. The highest post-War temperature is the 39.5°C which occurred in Słubice on July 30th 1994.

On average, the air temperature over the Silesian Plain and in Wielkopolska is expected to exceed 35°C (e.g. Wroclaw 35.8°C) once a decade. Equally, there is only likely to be a yearly maximum air temperature of less than 30°C there once a decade. The highest maxima for air temperature on the coast are 3–4°C lower than inland. In contrast, the lowering to be noted for this indicator as one moves east is not very great, while the considerable decline in maxima south towards the mountains is mainly a reflection of increasing altitude. On 1602 m Mount Śnieżka for example, the extreme air temperature recorded peaked at 23.6°C, as compared with the 23.0°C noted for 1985 m Kasprowy Wierch in the Tatra Mountains.

All of the stations studied present similar variability for the absolute maximum of temperature (Fig. 8). There is a downward trend of 3–4°C across the

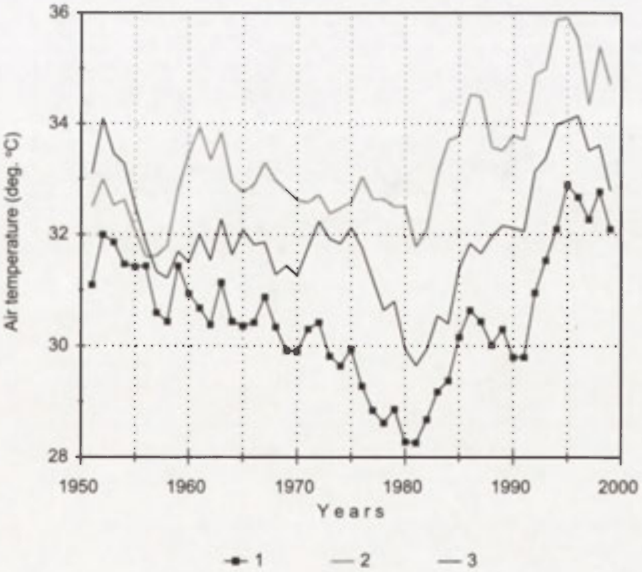

Figure 8. Long-term variability to the absolute maximum of air temperature at selected stations – moving 5-year averages (1951–1999).
Moving averages: 1 – Suwałki, 2 – Słubice, 3 – Warszawa.

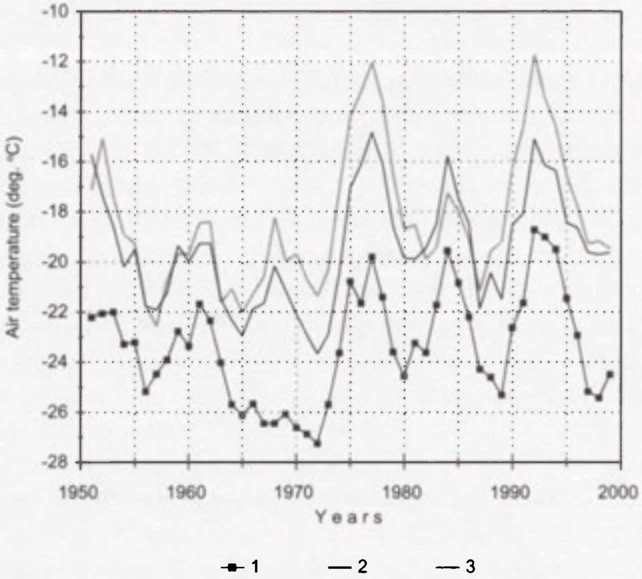

Figure 9. Long-term variability to the absolute minimum of air temperature at selected stations – moving 5-year averages (1951–1999).
Moving averages: 1 – Suwałki, 2 – Słubice, 3 – Warszawa.

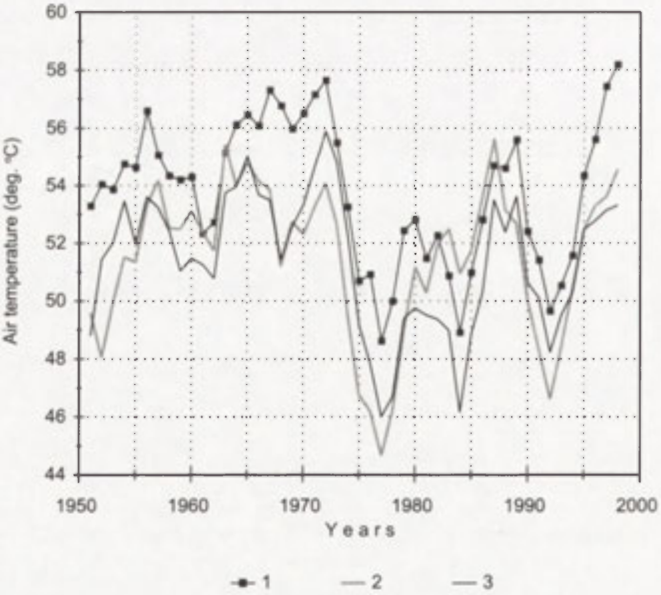

Figure 10. Long-term variability to the absolute amplitude of air temperature at selected stations – moving 5-year averages (1951–1999).
Moving averages: 1 – Suwałki, 2 – Słubice, 3 – Warszawa.

period 1951–1981, as compared with an upward trend of more than 4°C from 1982 onwards, with a maximum in the years 1993–1997. 1973–1985 inclusive were years of a marked cooling, with the Suwałki station not noting absolute maxima in excess of 30°C for 5 years in succession.

According to D. Kuziemska (1983), the lowest minimum air temperature ever recorded in Poland was the –41.0°C noted in Siedlce on January 11th 1940. Falls below –40°C were also recorded on February 10th–11th 1929 at several weather stations situated in concave landforms (Żywiec –40.6°C, Olkusz –40.4°C, Sianki –40.1°C). In the post-War period, the lowest temperature noted at the stations under analysis was the –35.8°C recorded at Rzeszów-Jasionka on February 28th 1963. Still lower values have in fact been obtained in the mountain basins (–37.6°C in Jabłonka on February 27th 1964 and –36.9°C in Jelenia Góra on February 10th 1956). However, many places in central and western Poland have not recorded falls below –30°C (e.g. Gorzów Wielkopolski with its absolute low of –27.1°C). The warming influence of the Baltic is exceptionally clear, with Hel never having recorded a value below –20.0°C, and Świnoujście none below –23.6°C. Indeed, there are years in which the coastal stations have failed to record any minima below –5°C. Overall, eastern Poland may be expected to record falls below –28°C once a decade, western Poland falls below –21°C with this degree of regularity, and the coast declines in air temperature below –17°C. Only in the mountain basins and in the north-east is there a 10% probability of minima below –30°C being recorded.

The picture for changes among these absolute minima of air temperature is quite different from that obtained for maxima (Fig. 9). A contiguous period of low minima for absolute air temperature lasted between 1956 and 1972, while the years post-1973 witnessed a fundamental change to the rhythm. This took the form of considerable fluctuations over periods lasting around 7–8 years, with the most marked warming falling in the years 1977, 1984 and 1992, and the most distinct cooling in 1980, 1987–1989 and 1998.

It is the minima that determine the variability to long-term values for average annual amplitudes of absolute air temperature (Fig. 10). Thus, there was a distinct and uniform period of high amplitude in the years 1951–1972, attesting to clear continentality of climate. 1973 saw the start of a major change for this element, with the absolute range between maxima and minima in the years 1973–1977 inclusive being around 10 degrees smaller, something that suggests a greater oceanicity of Poland's climate. 1977, 1984 and 1992 were the years with the most limited range between maxima and minima, while a renewed (6°C) increase in annual amplitude was only observed as recently as in the years 1994–1998.

EXTREME PRECIPITATION EVENTS

It is the characteristics of rainfall, from among all the climatic elements, that show the greatest variability over both time and space. Analysis for the purpose

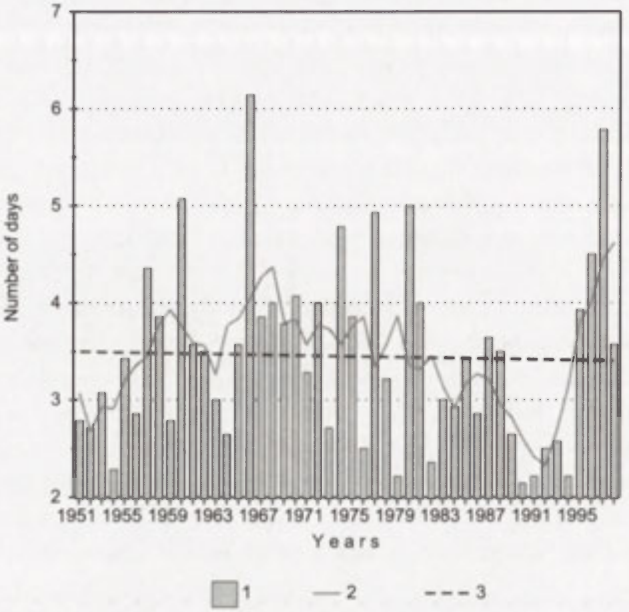

Figure 11. Long-term variability to the number of days with atmospheric precipitation > 20 mm – averages from 14 stations (1951–1998).
1 – annual number of days, 2 – moving averages (5-year), 3 – linear trend.

of the present study made use of two such characteristics for precipitation extremes that were averaged for data from 14 stations distributed evenly across the country (Fig. 11). The number of days with mean precipitation of over 20.0 mm has shown marked fluctuations over the last 50 years, but no clear trend. There is thus no basis for stating that the frequency of extreme precipitation events has been increasing.

Days with heavy precipitation were few in the years 1951–1956, while the period 1957–1981 inclusive was marked by a greater number of days with heavy precipitation as defined above – reaching 6 in 1996. The years 1982–1994 were basically dry years, while the time from 1995 onwards has seen a renewed increase in the average number of days with heavy falls – to almost 6 in 1997. A similar rhythm to changes in daily maximum precipitation has been observed in the Carpathians (Cebulak 1997).

In turn, where the number of days without rain is concerned, the long-term variability averaged for Poland shows a clear downward trend (Fig. 12) – from 208 days without precipitation in the years 1951–1955, to less than 190 days in the years 1995–1999. The lowest number of days without precipitation of all was the 162 noted in 1970, while the greatest number was 238 precipitation-free days in 1982, 1959, 1951 and 1953. Overall, however, there were irregular fluctuations

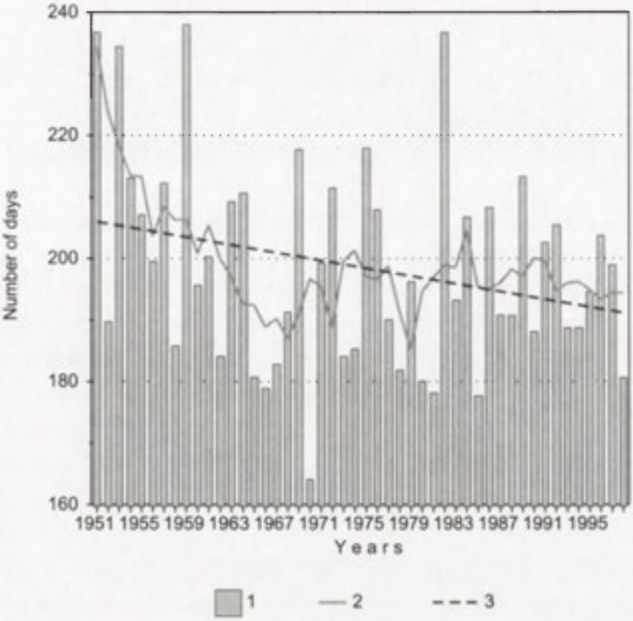

Figure 12. Long-term variability to the number of days without atmospheric precipitation – averages from 14 stations (1951–1998).
1 – annual number of days, 2 – moving averages (5-year), 3 – linear trend.

in the number of precipitation-free days from year to year, with no periodicity being visible.

SUMMARY

The recent variability to indicators of westerly and southerly circulations and cyclonicity in Poland has not been sufficient to depart markedly from the range to such variability noted in earlier periods (data for 1873 onwards). These changes are the result of a considerable dynamic to pressure sytems which is manifested in the course of extremes of atmospheric pressure and the frequency of occurrence of exceptionally high values for changes in pressure greater than 5.0 hPa over 3 hours.

In turn, the long-term course for absolute maxima of temperature shows a high degree of levelling-out of curves, with a larger fall in temperature over the period 1977–1982, followed by an upward trend culminating in the years 1992 and 1994. A considerable lowering of temperature maxima in the years 1975–1980 is hard to explain, but is probably associated with increased cloud cover over Central Europe. The long-term progress of the course for absolute minima of temperature reveals two cooler periods in Poland: in the years 1951–1970 and

1978–1987; as well as two warmer periods culminating around 1974 and 1989–1990. While the fluctuations are quite major, no clear trend may be divined. This said, there are many places, including the cities of Warsaw and Wrocław, in which the period 1973–1998 differed from earlier ones in a clear increase in the variability of absolute minima from year to year. This was reflected in increased absolute amplitude of temperature in different years.

The study of the variability to precipitation phenomena took account not only of extreme totals from year to year, but also in particular of daily maxima. The variability to the frequency of occurrence of days with more than 20 mm is interesting, as the data for Poland over the last half-century suggest two periods of intensification, especially in the south – in the years 1958–1980 and from 1995 onwards (Cebulak et al. 1996; Cebulak 1997).

In short, it is at present hard to offer unambiguous confirmation of the hypothesis that extreme climatic events have become more frequent in the last decade. It would seem rather that their incidence has remained very much linked to irregular fluctuations of atmospheric circulation. Moreover, many of the meteorological phenomena of natural-disaster rank have been local in their scope, frequently escaping direct observation. It is for this reason that further methodological work needs to be carried out to draw up databases on extreme climatic events using voluntary observations from every local community in Poland, along with satellite and radar data. Long-term study of the variability to extreme phenomena requires that all the instrumented measurement sequences be made fully uniform (Niedźwiedź and Ustrnul 1997). Some of them are still spread around a large number of different archives, including abroad (especially in Germany and Austria).

Trends to the variability of selected extreme characteristics of the 20th century climate have also been presented for the United States (Karl et al. 1996). Proposed as a measure of the frequency of extreme phenomena there is the so-called "Climate Extremes Index" (CEI). Karl et al. reported significant changes to this index beginning around the year 1970, especially where increased precipitation and temperatures are concerned. In Poland, the marked change for thermic maxima proceeded after 1982, as linked with major changes in the distribution of cloud cover. In contrast, the absolute temperature minima and amplitude experienced major change from 1973 onwards as a result of greater oceanicity of the Polish climate.

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CHANGES IN THE INTENSITY AND FREQUENCY OF OCCURRENCE OF DROUGHTS IN POLAND (1891–1995)

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ABSTRACT: Research by the Poznań Branch of the Institute of Meteorology and Water Management (IMGW) sought to analyse the phenomenon of the occurrence of droughts. The identification and characterisation of dry spells was performed on the basis of a unified methodology taking into consideration atmospheric conditions, and the situation regarding surface and underground waters. Attention was paid to changes in the intensity and frequency of occurrence of this phenomenon in Poland. The general trend to the changes, was ascertained and a cyclical character or fluctuations to the phenomenon in the course of the analysed period sought.

KEY WORDS: atmospheric drought, hydrological drought, intensity, frequency, changes, Poland.

INTRODUCTION

Investigations at the Poznań Branch of the Institute of Meteorology and Water Management (IMGW) in the 1990s sought to analyse the phenomenon of the occurrence of droughts (Farat et al. 1995). The identification and characterisation of dry spells was performed on the basis of a unified methodology taking into consideration three mutually-interlinked environmental elements: atmospheric conditions and the condition of surface and underground waters, over the longest possible period beginning in 1891. In the course of studies attention was paid, inter alia, to changes in the intensity and frequency of occurrence of this phenomenon in Poland. The general trend to the changes was sought, along with cyclicity and fluctuations in the course of the analysed period and selected values characterising variability that could be subjected to statistical analysis. The results of the research are presented below in the form of a short communiqué.

OBSERVATIONAL MATERIALS AND METHODS OF PROCESSING

The following principles were adopted in the identification of drought phenomena:

ATMOSPHERIC DROUGHTS

Climatic water balance was adopted as the basis for evaluating the degree of development of an atmospheric drought. This index was calculated according to the formula:

$$K = P - EP,$$

where: K – climatic water balance [mm],
P – atmospheric precipitation [mm],
EP – potential evaporation [mm] after the formula from N. N. Iwanow and Penman:

$$EP = 0.0018\ (25 + T)^2(100 - f),$$

where: T – mean air temperature [°C],
F – mean relative air humidity [%].

On the basis of trials performed the value of the adopted climatic water balance was assumed to be 200 mm/year, below which the deficit of precipitation indicates the occurrence of an intense atmospheric drought.

HYDROLOGICAL DROUGHTS

SURFACE WATERS

Depending on the period the occurrence and course of the droughts (low-flow periods) associated with surface waters were based on the analysis of daily water states (1891–1950) or flows (1951–1995). Calculated for each profile was a limiting state (or flow) – N_G, i.e. mean of the lowest annuals over a long period. A series of daily states (or flows) with values lower than the limiting ones of duration 20 days or more was treated as a low-flow period.

UNDERGROUND WATERS

The basis for the identification of dry spells taking in the first horizon of ground waters was the assumption that, over at least 20% of the country, the level of occurrence of the first horizon of underground waters (mean monthly water states at analysed points) is more than 50 cm lower than the long-term mean state for a given month of the year.

Depending on the analysed element of the environment, and on the basis of the methodology presented earlier, initial measurement materials for 50–80 points evenly distributed throughout Poland within her current borders were analysed. Throughout the study, the hydrological year was accepted as the basic period of analysis. Because of the availability of measurement data for the entire area of Poland, changes in the intensity and occurrence of the analysed phenomenon were assessed for the following periods:

- Atmospheric droughts: period 1891–1995,
- Hydrological droughts associated with surface waters: period 1901–1995,
- Hydrological droughts associated with underground waters: period 1951–1995.

For the above-identified periods, the following selected values characterising the occurrence of droughts in Poland were subjected to statistical analysis:

- for each of the three spheres of the analysed geographical environment, the maximum area of Poland affected by drought expressed as a percentage of the total area. The value was determined and then analysed for each year of the examined period, even if a given year was characterised by non-fulfilment of the criterion concerning the area of the country on which the phenomenon was to have occurred,
- for atmospheric droughts and hydrological droughts associated with underground waters, the number of months with drought in years in which the phenomenon occurred,
- for hydrological droughts associated with surface waters (for a year in which a drought occurred), the maximum duration of the phenomenon (considered in relation to individual measurement points).

RESULTS AND DISCUSSION

Overall, the years 1891–1995 experienced a total of 75 identifiable atmospheric droughts, 24 years with hydrological drought associated with surface waters and 17 hydrological droughts associated with underground waters. This considerable difference between the numbers of atmospheric and hydrological droughts identified may primarily be attributed to the very nature of the phenomenon described. Atmospheric droughts are much more likely to be affected by the direct influence of changeable weather conditions than hydrological droughts, especially those associated with underground waters, which are characterised by greater inertia.

The mean frequency of occurrence of a hydrological year with an atmospheric drought was lower in years the 1951–1995 (one drought year every 1.7 years) than over the entire analysed period (every 1.6 years). In the case of hydrological droughts associated with surface waters, the situation was the reverse: a hydrological year with a drought occurred less frequently over the entire analysed period (on average, one year with drought every 4 years) than in the last 45 years (every 3.2 years). In the same period of time, a hydrological year with droughts associated with underground waters occurred on average every 2 years.

The longest periods during which droughts occurred in successive hydrological years were 1949–1954 (6 years) and 1988–1993 (6 years) in the case of atmospheric drought; 1950–1954 (5 years) for hydrological droughts associated with surface waters and 1989–1994 (6 years) and 1951–1955 (5 years) for those associated with underground waters. On the other hand, the longest periods without drought (in successive hydrological years) were the periods: 1936–1939 (4 years) and 1965–1968 (4 years) for atmospheric drought; 1970–1982 (13 years) and 1912–1929 (9 years) for hydrological drought associated with surface waters and 1975–1982 (7 years) for that associated with underground waters.

The possibility of observing changes in the intensity of the consecutive droughts which occurred in the period 1981–1995 was investigated by analysing the duration of droughts, number of months with droughts in successive years and the area of the country occupied in periods of the maximum spatial development of this phenomenon.

The longest atmospheric droughts took place in the periods: XI 1958 – XI 1959 (13 months), III 1953 – III 1954 (13 months), XI 1968 – X 1969 (12 months) and earlier II – X 1921 (9 months). In general, longer periods with atmospheric droughts can be said to have begun to occur in the last 45-year period. The longest hydrological droughts associated with underground waters occurred: VII 1989 – V 1991 (23 months) and X 1953 – IV 1955 (19 months). They occurred in periods characterised by a high frequency of drought occurrence in this sphere of the geographical environment, namely in the 1950s (in the period from IX 1951 – IV 1955 a total of 33 months with drought) and at the end of the 1980s and beginning of the 1990s (from VII 1989 – XII 1993 – 49 moths with drought).

When studying the problem of the duration of drought in the case of surface waters, analysis concerned the duration of the longest low-flow periods selected from among those which were observed in a given year and in observed profiles. The average duration of the longest low flow periods was slightly shorter during the last 40-year period (on average: 87.7 days) than in the entire analysed period (average: 92.1 days). The longest low-flow periods, lasting over 170 days occurred in the following years with hydrological drought: 1911 (200 days), 1947 (171 days), 1951 (181 days), 1953 (201 days), 1959 (191 days), 1983 (238 days), 1990 (182 days) and 1992 (178 days).

In the case of atmospheric droughts, as well as hydrological ones associated with underground waters, analysis concerned the number of months with a drought in a hydrological year in which the phenomenon occurred. In the case of atmospheric droughts, there were 21 situations in which there were at least 6 months with a drought in one year. These situations were distributed fairly uniformly over the entire analysed period. In years 1928–1929, 1953–1954 and 1963–1964 they occurred year after year. The greatest number of months with

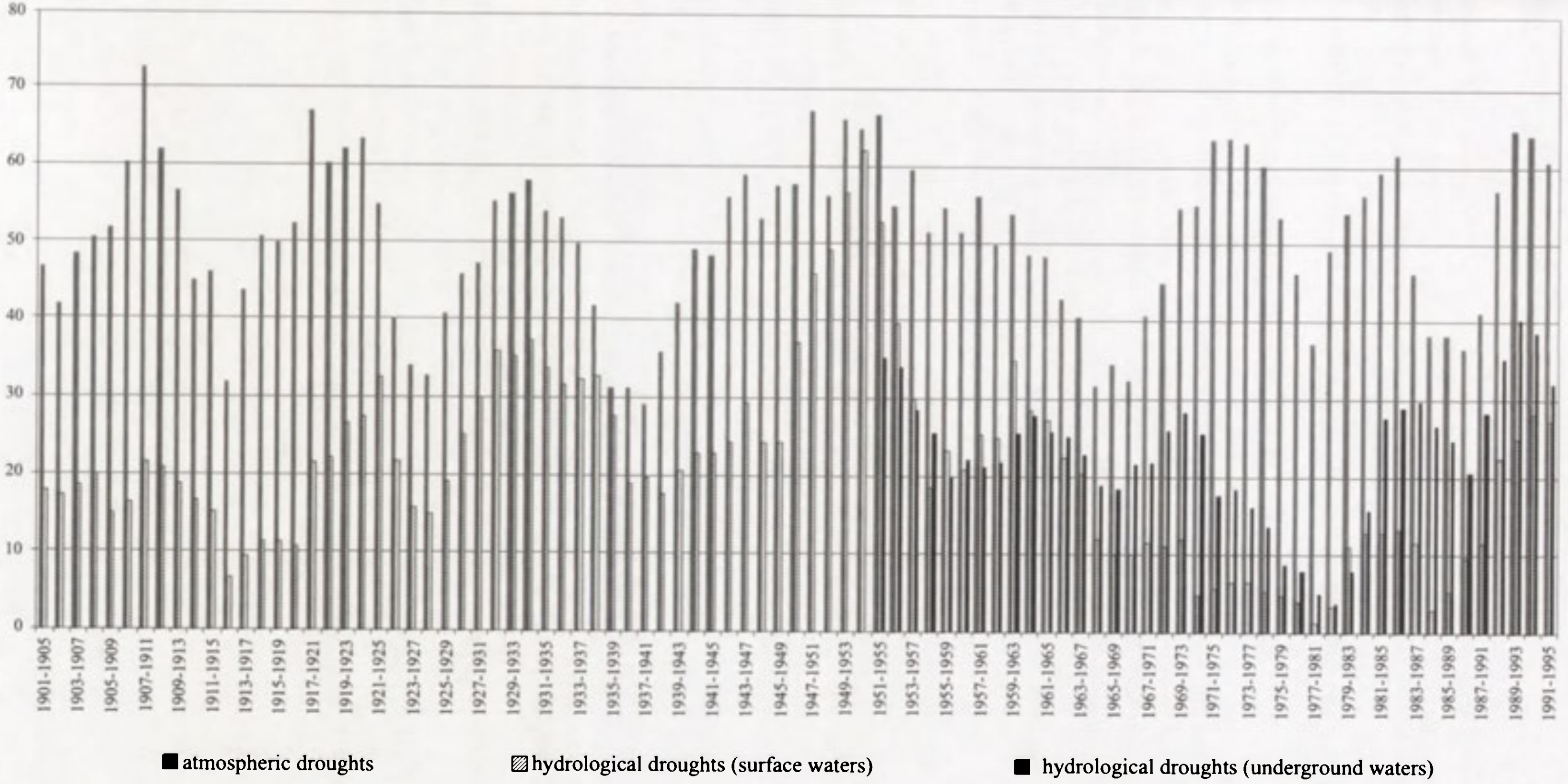

Figure. 1. Area of country experiencing drought (%).

drought (10) occurred in 1954. The variability of this index over time became more conspicuous when mean quantities of months with drought in movable 5-year periods were calculated. A distinct rhythm becomes quite apparent here with main maxima identifiable in the years 1894, 1909, 1919, 1932, 1942, 1952, 1962, 1974, 1984, and 1991 which allows for the determination of the mean cycle length at 10.5 years.

In the case of underground waters, there were 11 instances with at least 6 months of drought during one year. Such situations occurred primarily in the course of the first and last several years of the last 45-year period. In the periods 1954–1955, 1984–1985 and 1990–1993 these situations occurred year after year. In the years 1952, 1954 and 1990 twelve months with a hydrological drought associated with underground waters occurred. As in the case of atmospheric droughts, here also a certain rhythm to the time course of variability in values for this parameter became visible after the mean number of months with drought in movable 5-year periods was calculated. It was possible then to identify the following main maxima in the years 1953, 1962, 1971, 1983 and 1991, allowing for the determining of the mean cycle length at 9 years.

The percentage of Poland occupied by droughts in periods of their occurrence was analysed in relation to both atmospheric and hydrological droughts.

The biggest areas of Poland experiencing atmospheric drought were observed in the years 1992 (92%), 1951, 1959 and 1982 (91%) and 1921 and 1947 (87%). In the case of hydrological droughts associated with surface waters, such situations occurred in the years 1959 (80%), 1951 (70%), 1950 (64%), 1952 (62%), 1930 (31%) and 1992 (56%), while in the case of droughts associated with underground waters, in the years 1954 (55%), 1970 (50%) and 1992 (48%). The time variability to this parameter is shown in Figure 1, which presents mean movable areas of Poland expressed as a percentage of the country's total area taken up by droughts in periods of their occurrence. The main maxima and minima visible in the course of movable means portraying drought ranges of those areas in the three analysed spheres of geographical environment are, to a considerable extent, convergent in time. And so, for instance, the main maxima characterising areal variability to the occurrence of atmospheric droughts took place in the pentads 1897–1911, 1921–1925, 1930 1934, 1943–1947, 1950–1954, 1959–1963, 1972, 1976, 1982–1986 and 1990–1994. So the observed variations of average period length amount to 10.5 years.

CONCLUDING REMARKS

- The performed statistical analyses comprised some selected values characterising frequency and intensity variations to the occurrence of droughts in Poland in the years 1891–1995. Approximations of long-term changes in the analysed characteristics were made using equations of linear regressions for this purpose. It emerged that change trends for these characteristics considered for the entire period turned were statistically non-significant.

- Droughts, which were identified in the first part of the analysed long-term period, were characterised by higher regularity of occurrence and were also similar with regard to such parameters describing them as duration or the area occupied. On the other hand, the period beginning with the 1940s until the 1990s was characterised by quite considerable contrasts in the variability of the analysed phenomenon. For example, this period witnessed the longest periods with both uninterrupted series of years with droughts and without them. Moreover, it was also in this period that 75% of the longest low-flow periods lasting more than 170 days occurred, as well as 66% of droughts characterised by the largest area on which the phenomenon developed, etc.
- Analysis of the variability to the selected characteristics describing changes in the frequency and intensity of the droughts occurring in Poland showed them to exhibit a tendency towards an erratic cyclicity and to be characterised by an amplitude which changes over time and a diversified phase variation. Attention was also paid to a trend to the occurrence of 2–3-year rhythms associated with the appearance of special cases of dry spells 9–10.5-year longs, associated, for example, with the number of months with both atmospheric and hydrological drought (associated with underground waters) in years when this phenomenon occurred, or with 40-year periods associated with a tendency for the occurrence of the longest low-flow periods or droughts associated with underground waters. It is thus possible to invoke certain analogies with the rhythms affecting atmospheric precipitation (Boryczka 1984; Kożuchowski 1985; Jeż 1987; Michalska 1997) or, further on, atmospheric circulation (Jokiel 1997).

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ANALYSIS OF RESULTS OF GLOBAL CLIMATE MODELS FOR CENTRAL EUROPE AND POLAND

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ABSTRACT: The paper presents an evaluation of climate simulations by the ocean and atmosphere general circulation models from the IPCC DDC for two regions: the Central European area and Poland. The comparisons have concerned air surface temperature, precipitation and wind speed. Control runs of the models for the period 1960–1989 and the results of the "Greenhouse Gas plus Sulphate" experiment for the next century 2000–2099 have been analysed. Re-analysed observed data have been used as the reference distributions for climate parameters.

KEY WORDS: climate simulations, general circulation models, air temperature, precipitation, wind.

INTRODUCTION

To envisage various possible menaces of the natural environment, the governments of many countries have been designating considerable funds for research on climate and its possible changes. The co-ordinating institution for investigations of climate system evolution is the Intergovernmental Panel on Climate Change (IPCC). The last two years the Data Distribution Centre (DDC) has been established according to an initiative of the IPCC Task Group on Climate Scenarios for Impact Assessments. The Centre is located at the University of East Anglia at Norwich and is maintained in co-operation with the German Climate Research Centre (DKRZ) in Hamburg. The main task of the DDC is to facilitate the distribution of a consistent and up-to-date set of climate scenarios for the purposes of the evaluation and assessment of the impact of possible climate changes on various environmental elements and processes.

The data are on the DDC server[1] on the Internet, and there is also a possibility of receiving the set of data files on a CD. Available at this time are the results for simulations from eight models (Tab. 1) for three experiments: control (CI), the "Greenhouse Gas" scenario (GG) including all greenhouse gases and the "Greenhouse Gas plus Sulphate" scenario (GS), additionally taking into account the negative interactions with sulphate aerosols. The lengths of experiments are different (Fig. 1). Figure 1 also indicates the scenarios for which *ensemble*[2] experiments have been carried out and the results of these runs made available on the DDC server.

Table 1. Models in the IPCC DDC.

Model	Institute	Country
CSIRO	Australia's Commonwealth Scientific and Industrial Research Organisation	Australia
ECHAM4	The German Climate Research Centre	Germany
HadCM2	The UK Hadley Centre for Climate Prediction and Research	United Kingdom
HadCM3	The UK Hadley Centre for Climate Prediction and Research	United Kingdom
CCCM	Canadian Center for Climate Modelling and Analysis	Canada
GFDL	Geophysical Fluid Dynamics Laboratory	USA
NCAR	National Centre for Atmospheric Research	USA
JCCSR	Center for Climate Research Studies	Japan

The models differ in their parameterizations of physical processes, numerical techniques applied in solving equations, horizontal and vertical resolution, orography and land-sea masks. Figure 2 shows the orography of the region of interest to us according to each model and, for comparison, the orography prepared by the NOAA[3] (ETOPO5[4]). The topography in the CCCM, CSIRO, and GFDL models is highly smoothed, the mean height above sea level lower than in reality. In the other models the topography is much more differentiated. The British models HadCM2 and HadCM3 have the most realistic topography. An interesting feature is the shoreline assumed in the models (Fig. 3). The shoreline of the Baltic and Mediterranean Seas can serve as good examples of the differences between models.

The aim of this paper was to analyse the results available from the DDC for two regions: the Central European area (5–40°E, 40–60°N) and Poland. The comparisons have been made for air surface temperature, precipitation and wind

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[1] http: //ipcc-ddc.cru.uea.ac.uk/index.html

[2] several model's integrations for different initial conditions

[3] National Oceanic and Atmospheric Administration

[4] ETOPO5, 1988, Data Announcement 88-MGG-02, Digital relief of the Surface of the Earth, NOAA, National Geophysical Data Center, Boulder, Colorado. The version of the data making up ETOPO5 is from May, 1988, with the exception of a small area in Canada (120-130 W, 65-70 N), which was regridded in 1990 (http: //www. ngdc. noaa. gov/mgg/global/seltopo. html).

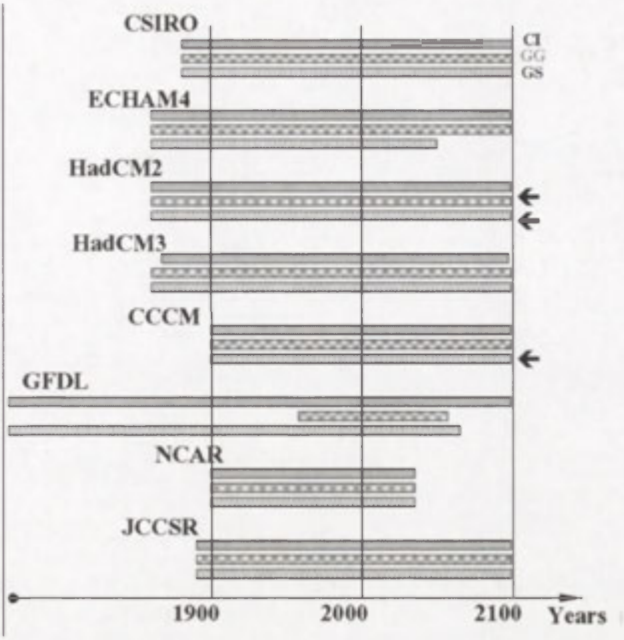

Figure 1. Models and experiments available in the IPCC DDC, for the experiments marked with arrows ensemble computations' results are available.

speed. Our assessments are based directly on the models' output, using data in grid points of each model (Fig. 3). No downscaling method has been applied, the intention of the authors being direct evaluation of models' behaviour in the regions of interest to us. For the purposes of intercomparisons for Poland the assumed regions in the spatial averaging of variables are as in Figure 3, according to the resolution of each model. Analysis has concerned the control runs in 1960–1989 and the results of the GS experiment for the period 2000–2099.

CONTROL RUNS IN 1960–1989

Monthly means for the three parameters air surface temperature, precipitation and wind speed have been analysed. Results of control experiments have been compared to re-analyses. The datasets used were: the NCEP[5] re-analyses (Kalnay et al. 1996) for temperature and wind speed, the Global Precipitation Dataset (Doherty et al. 1999), and the CRU Global Climate Dataset[6] from the University of East Anglia in the UK for precipitation and wind speed.

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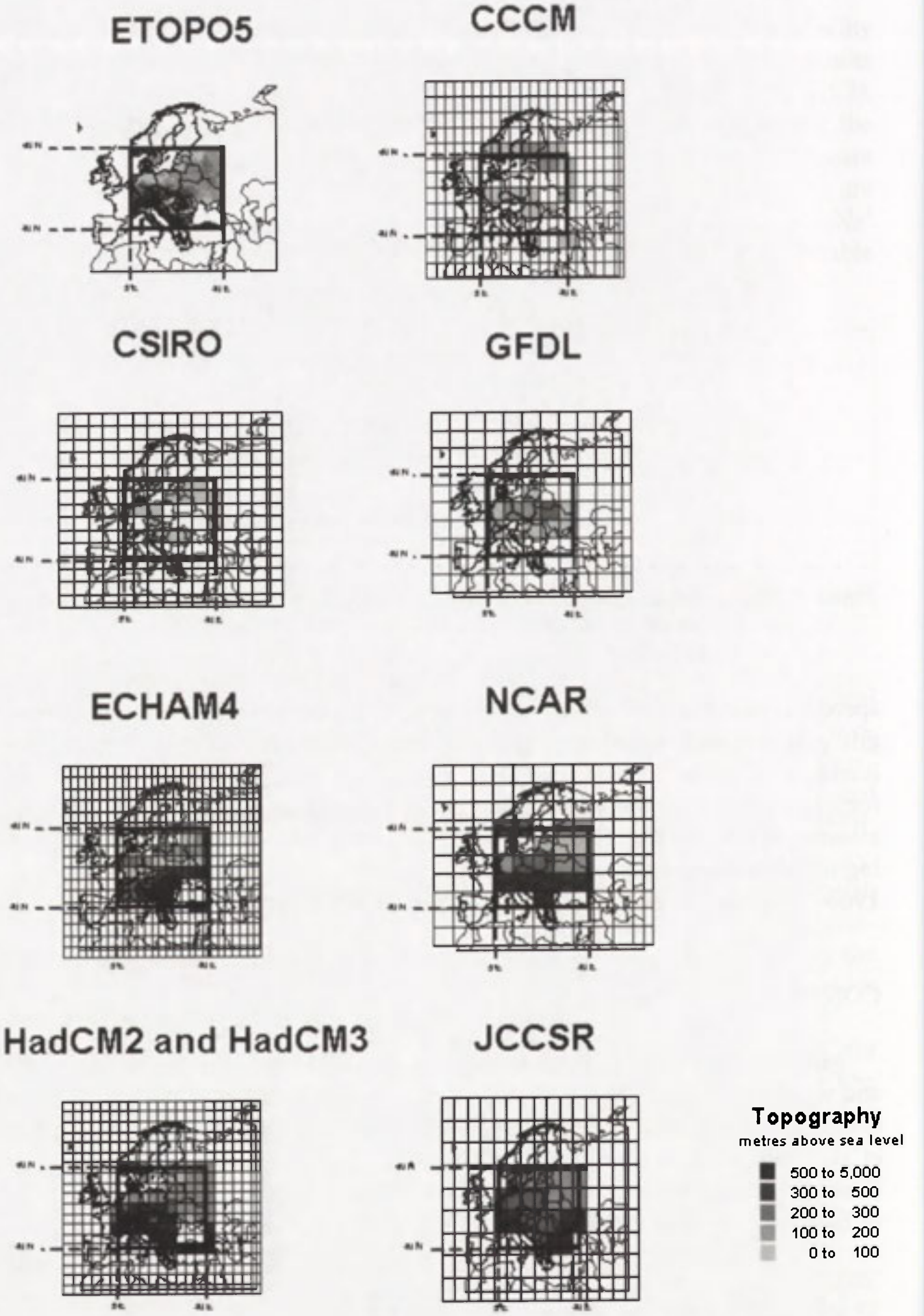
[5] National Centers for Environmental Prediction

[6] CRU Global Climate Dataset, The IPCC Data Distribution Centre (http: //ipcc-ddc. cru. uea. ac. uk/cru_data/).



ETOPO5

CCCM

CSIRO

GFDL

ECHAM4

NCAR

HadCM2 and HadCM3

JCCSR

Figure 2. Topography in models and as computed by the NOAA (ETOPO 5).

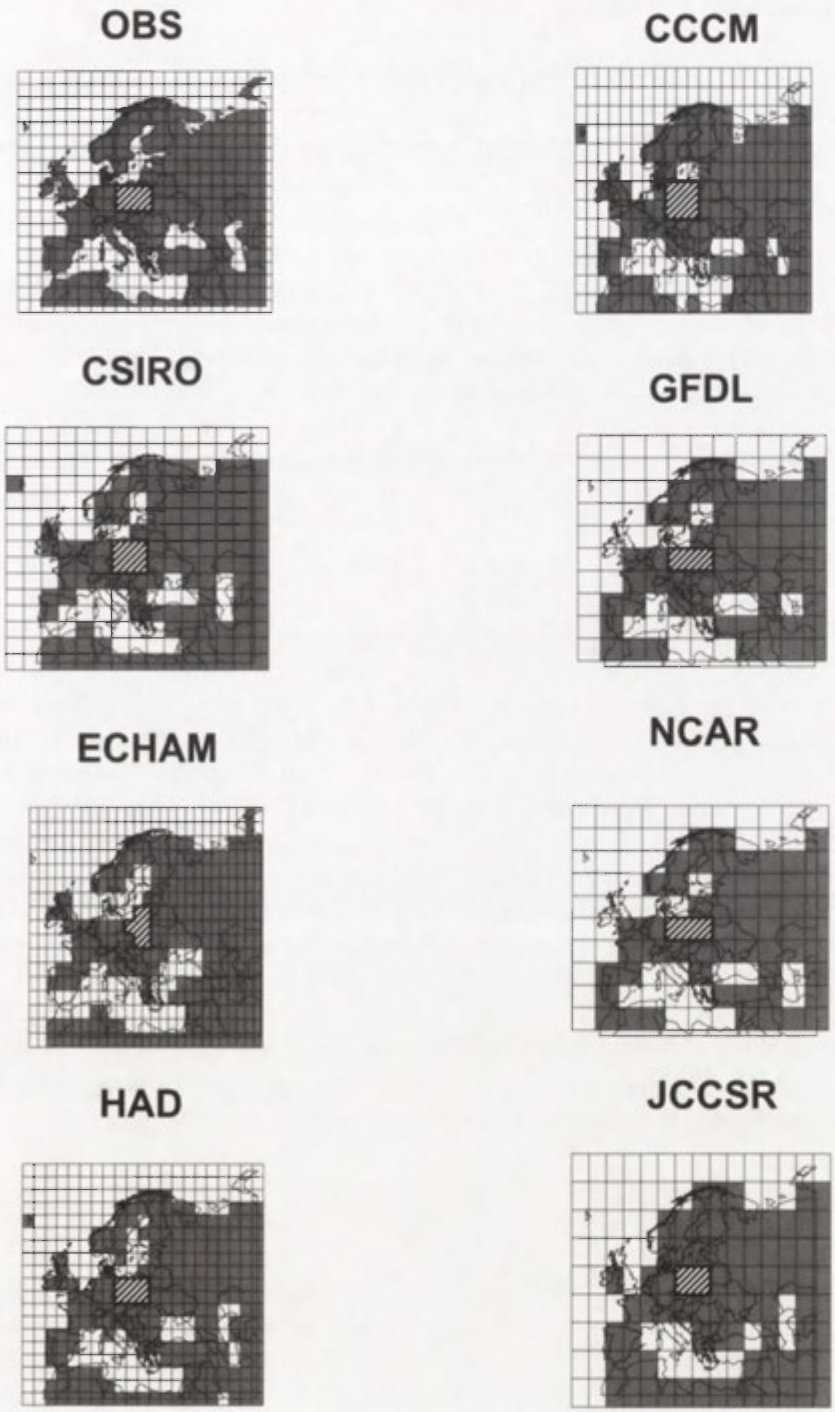


Figure 3. Land-sea mask in models and re-analyses OBS_GLOBAL (Doherty et al. 1999). Analysed regions: Central Europe (5–40°E, 40–60°N) and Poland (shaded area).

AIR SURFACE TEMPERATURE

Yearly distributions of monthly means for air temperature have a similar shape in all the analysed control simulations, except that the values are different. The CSIRO, HadCM3 and HadCM2 models give minimum differences between simulated and observed values. The NCAR projection is unrealistic and very different from the other simulations, the differences between the simulated and observed air temperature being even up to 12°C. In general, the range of variability of temperature in the Central European region is greater than in reality in all models (except CSIRO and GFDL) for example: the simulated maximum monthly mean value for temperature from the CCCM model is over 38°C while the corresponding value from re-analyses is about 25°C.

Figure 4 presents spatial patterns for annual means of simulated and observed temperature in the years 1960–1989. Generally, the temperature patterns fit to the re-analyses, the best accordance being obtained in the case of the HadCM3, HadCM2 and CSIRO models.

PRECIPITATION

The analysis of monthly means for precipitation in Central Europe and Poland showed that simulated values are in most cases underestimated in July, August and September, while being overestimated in the other months. The exception is the JCCSR model, with which simulated rainfall values are higher than those observed in summer months. The climate of the NCAR model is very wet during autumn, winter and spring – differences between monthly means of precipitation from the model and re-analyses are over 2 mm/day. Yearly distributions of rainfall are very similar in the: CCCM, CSIRO, GFDL, HadCM2 and HadCM3 models.

In the case of the 1960–1989 period, the best accordance between models and re-analyses for annual patterns of precipitation are those achieved with HadCM3, HadCM2 and GFDL (Fig. 5). In other cases the simulated patterns differ from the re-analyses.

WIND SPEED

Data for wind speed have been available from the ECHAM4, HadCM2, HadCM3, CCCM, NCAR and JCCSR models. The results from the models have been compared to re-analyses by two independent climate centres because the re-analyses themselves were markably different. In general, the simulated patterns for the wind speed correspond to observations in 1960–1989 (Fig. 6). The wind speed is higher during winter than in summer in the ECHAM4, HadCM2,

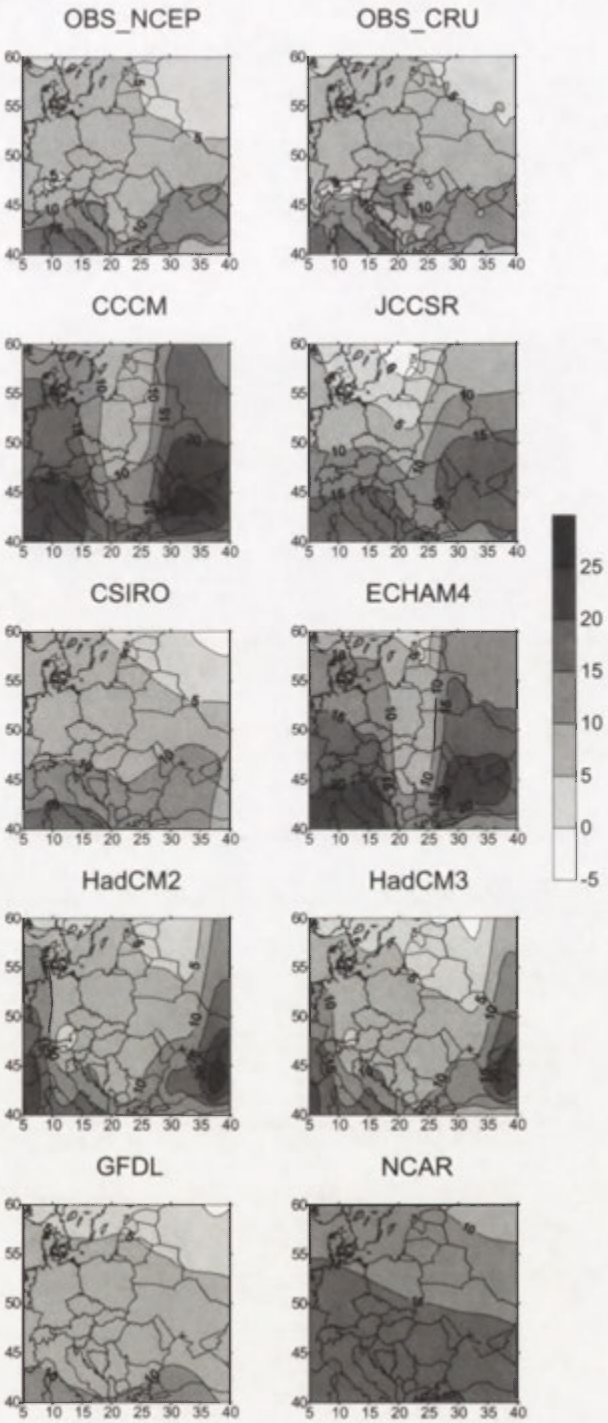


Figure 4. Annual means fields of air temperature [°C] for the modeled (CCCM, JCCSR, CSIRO, ECHAM4, HadCM2, HadCM3, GFDL and NCAR) and observed data (OBS_NCEP and OBS_CRU) averaged for the period 1960–1989.

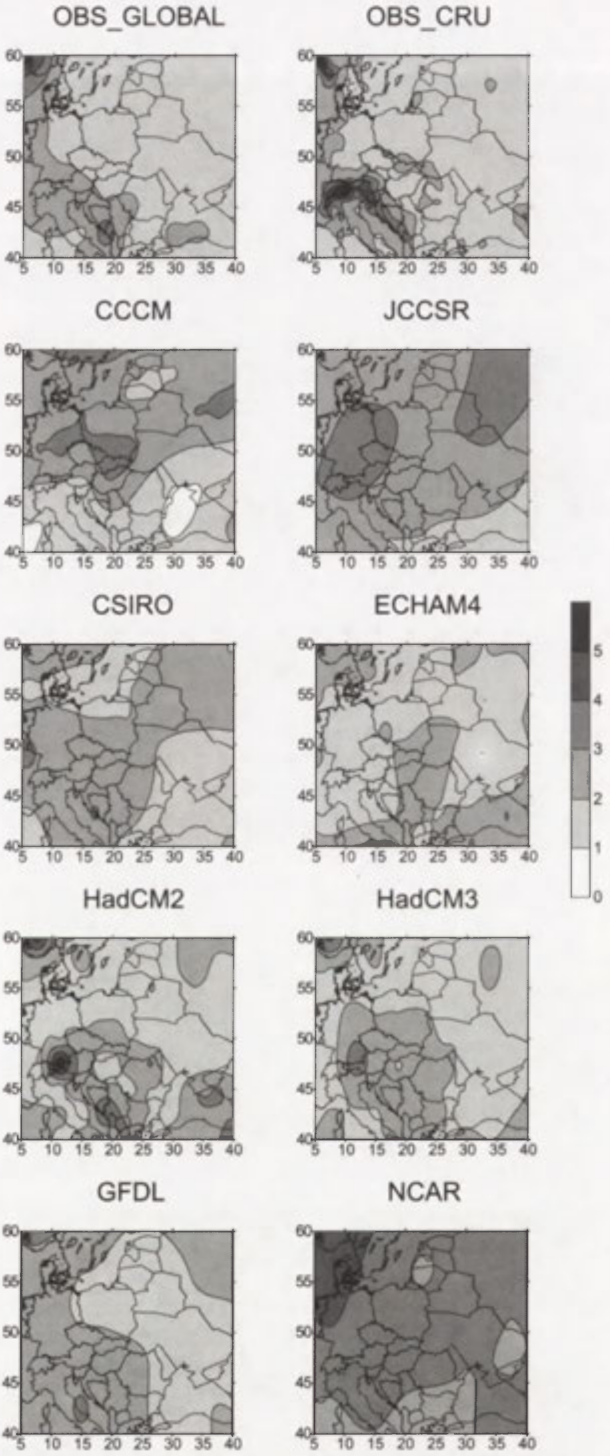


Figure 5. Annual means fields of precipitation [mm/d] for the modeled (CCCM, JCCSR, CSIRO, ECHAM4, HadCM2, HadCM3, GFDL and NCAR) and observed data (OBS_GLOBAL and OBS_CRU) averaged for the period 1960–1989.

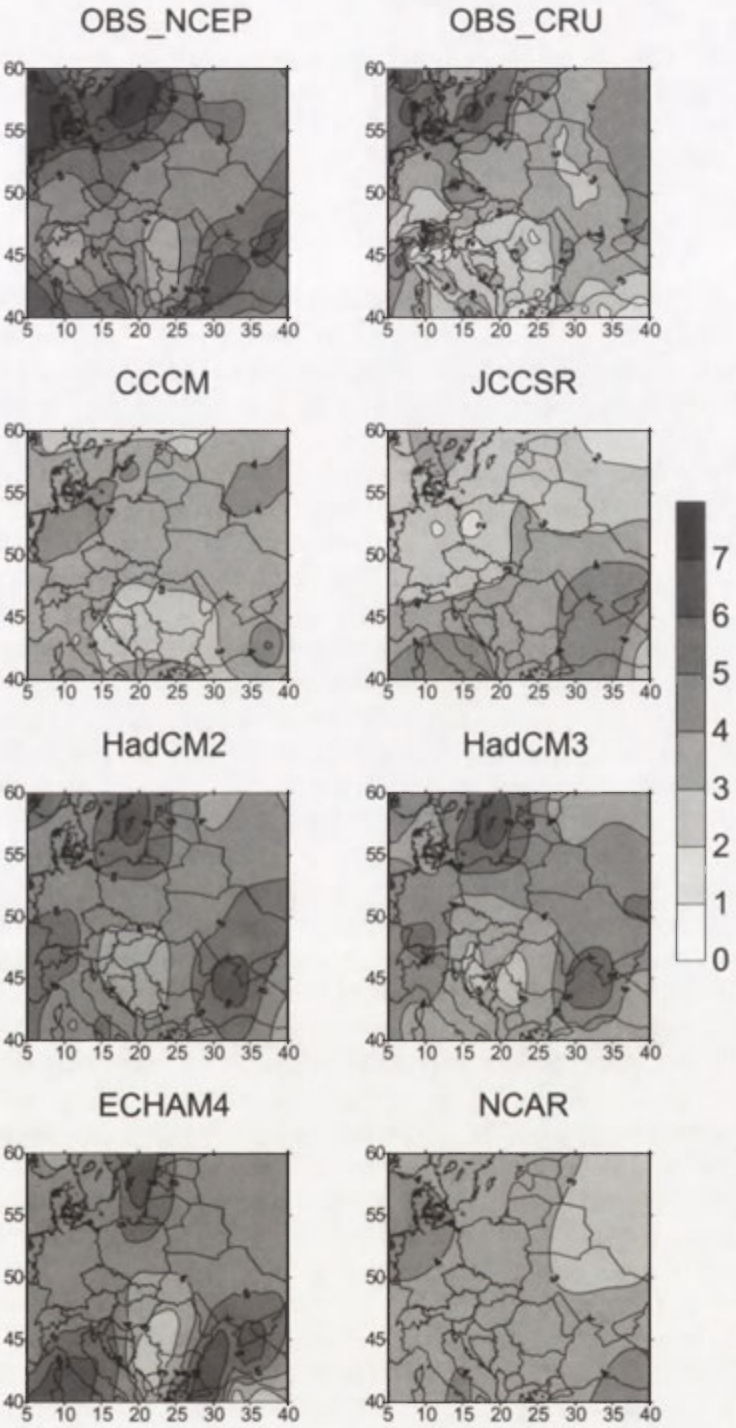


Figure 6. Annual means fields of wind speed [m/s] for the modeled (CCCM, JCCSR, ECHAM4, HadCM2, HadCM3 and NCAR) and observed data (OBS_NCEP and OBS_CRU) averaged for the period 1960–1989.

HadCM3 and NCAR models, and this is consistent with observations. Annual distributions of wind speed in both British models are in great measure similar to historical distributions based on the CRU Global Climate Dataset, however there is a shift towards higher values.

GS SIMULATIONS IN THE PERIOD 2000–2099

The role of sulphate aerosols in the atmosphere has increased in recent years, so the latest simulations by the ocean and atmosphere general circulation models include their emission into the air. All climate centres present in the DDC have performed such experiments, some of them are shorter (Fig. 1). The analysis of the GS simulation is based on spatially-averaged values of monthly means for air surface temperature and precipitation (Fig. 3). The values computed from simulations have been compared to historical data observed at Polish meteorological stations in the period 1951–1990, and derived from re-analyses in the years 1961–1989 (temperature – Kalnay et al. 1996, precipitation – Doherty et al. 1999).

Figure 7 shows time series for yearly means of air temperature and precipitation in the next century as simulated in the GS experiment. It is very noticeable that the NCAR model is an absolute exception whose, unrealistic overestimation of both parameters led it to be excluded from further comparisons. In the case of air temperature there are well-marked positive trends, the CCCM model giving the highest values, the JCCSR model the lowest. The JCCSR model shows the maximum variability in time, the NCAR and ECHAM4 models the minimum. Trends are much less clear in the case of precipitation. The CCCM model simulates maximum rainfall, the ECHAM4 model – minimum. The maximum variability in precipitation can be noted in the simulation of the GFDL model, the minimum – in that of the ECHAM4 model.

Monthly means for both parameters from the control and GS simulations in 2040–2049 have also been compared and related to historical data (Fig. 8). In general, the air temperature in the control simulations for 2040–2049 has an annual distribution close to the historical one, the smallest differences being obtained for the HadCM3 model, and the greatest for the JCCSR model. The Japanese JCCSR model simulates very low values for temperature during the winter months. Generally, all models simulate higher values for air temperature in the case of the GS scenario than in control runs. The maximum increases are mostly in winter and exceed 8°C in January (the JCCSR model). Minimum mean differences between the control run and the GS simulation for the analysed decade are to be noted for both the British and the Canadian models, maximum ones for the German and Japanese models. In the case of precipitation the picture is much more complicated. All the analysed models in most cases simulate greater values for rainfall in the considered decade than are observed nowadays.

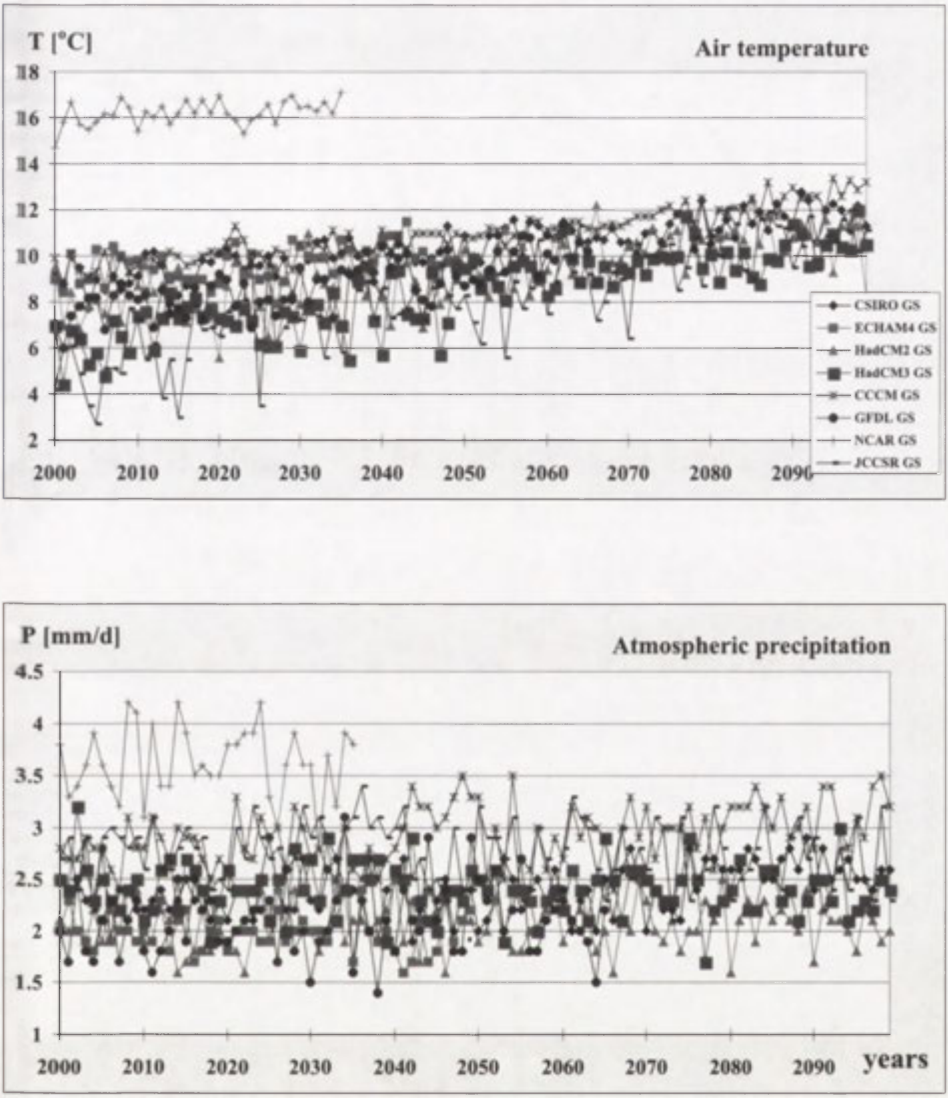
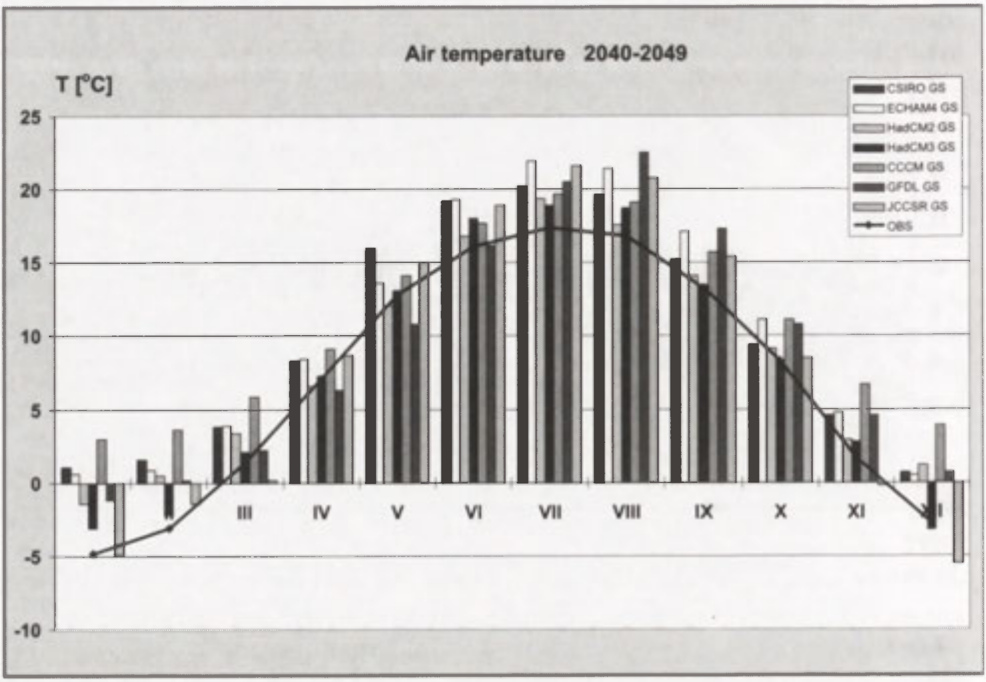


Figure 7. Annual means of temperature and precipitation in Poland (Fig. 3), GS – "Greenhouse Gas plus Sulphate" simulation in the period 2000–2099.

Simulated yearly distributions are generally very different from historical ones, the Australian and both British models giving the best approximations of the yearly run, the HadCM2 model the minimum mean error. The German model ECHAM4 simulates a reverse annual distribution of precipitation, the model's climate is very dry in summer, a characteristic feature of the all generations of models developed in the Max-Planck Institute in Hamburg. In general there are no distinctive trends to changes in rainfall in the GS scenario in comparison to the control run.



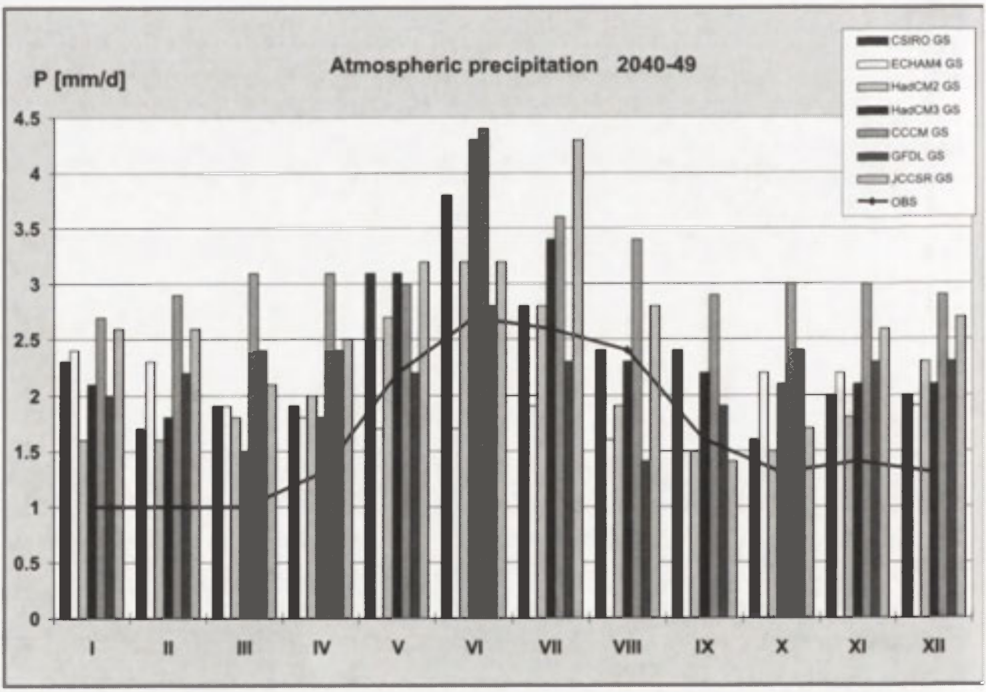


Figure 8. Monthly means of temperature and precipitation, GS – "Greenhouse Gas plus Sulphate" simulation in the period 2040–2049.

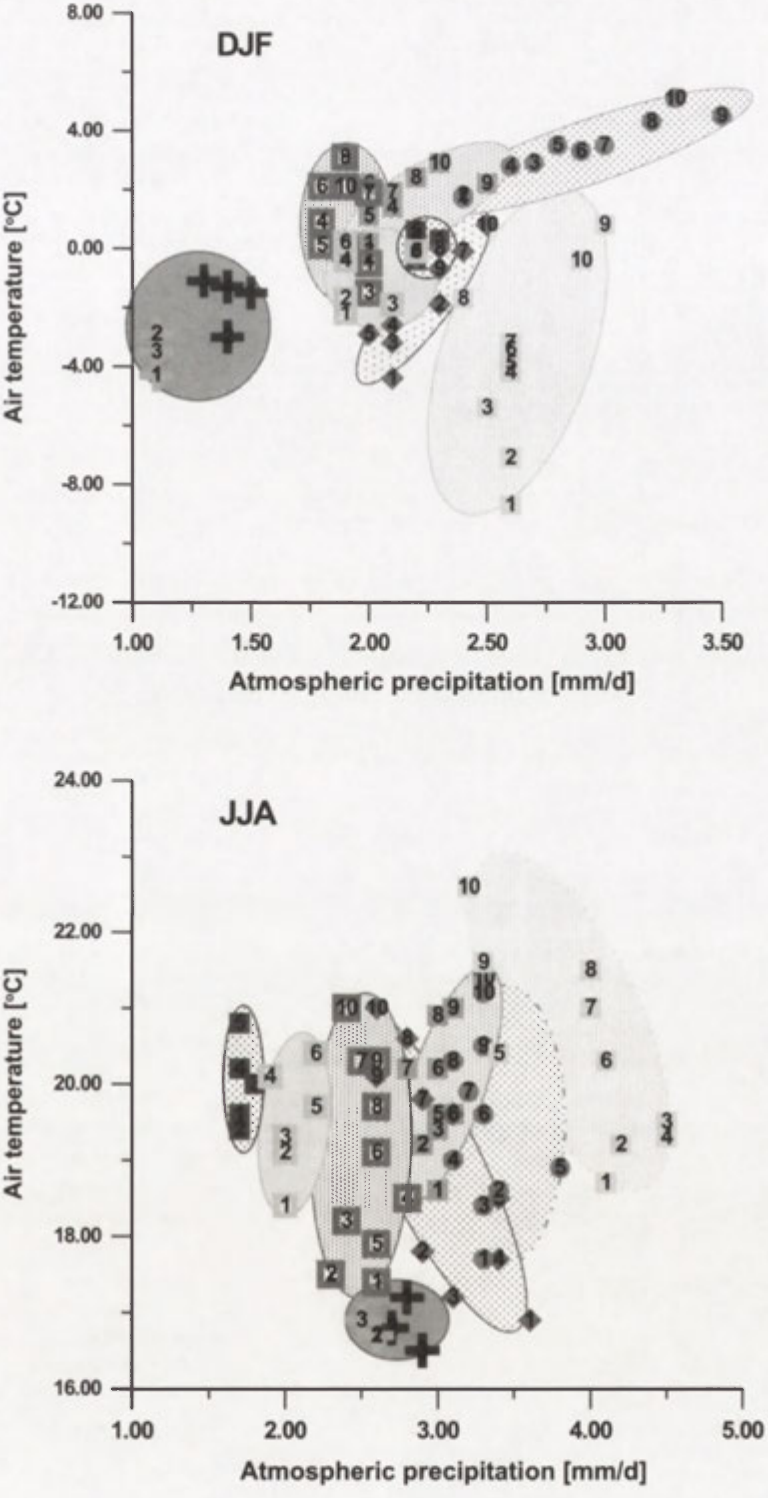


Figure 9a. Synthesis of GS – "Greenhouse Gas plus Sulphate" simulation for Poland in the period 2000–2099.

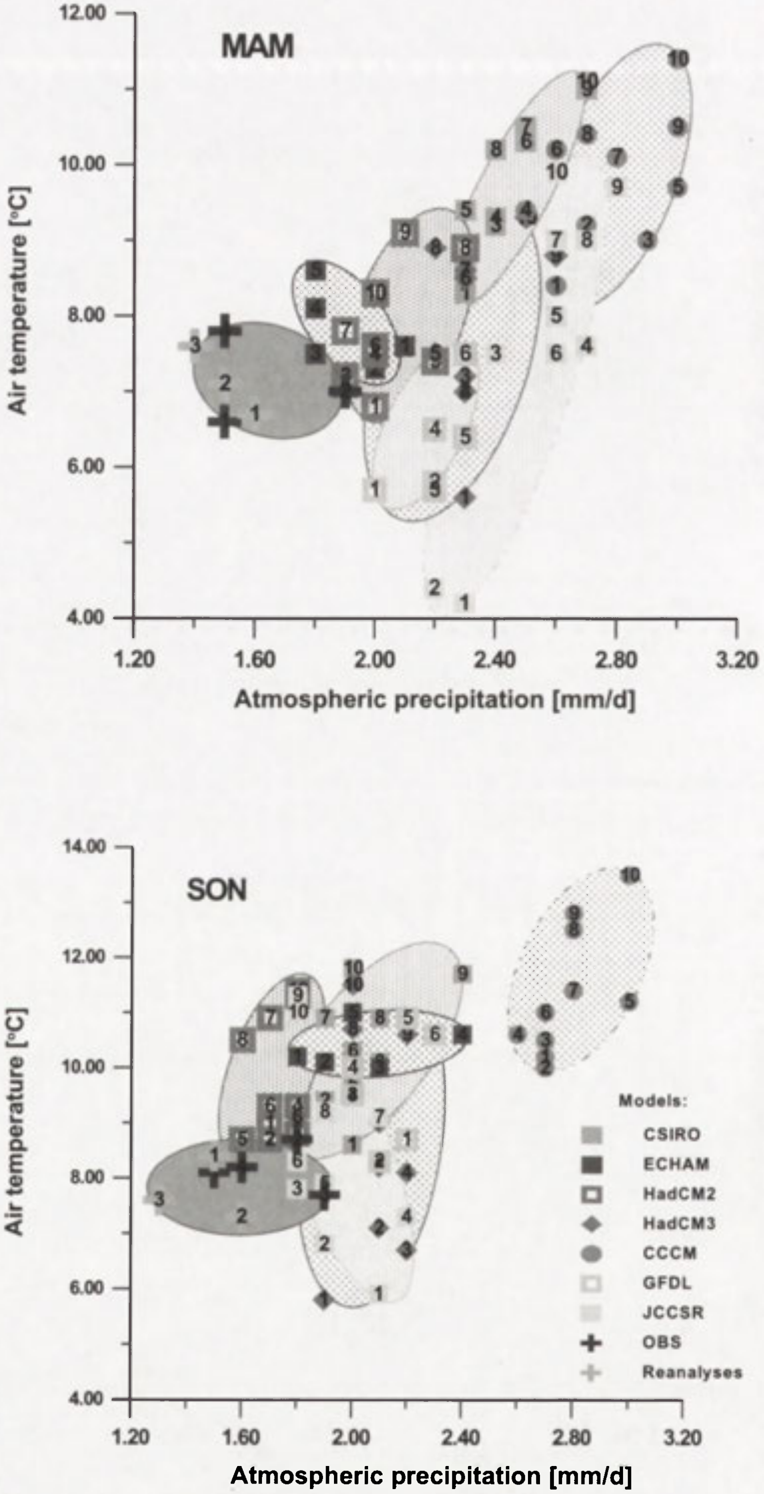


Figure 9b. Synthesis of GS – "Greenhouse Gas plus Sulphate" simulation for Poland in the period 2000–2099.

Figure 9a, b shows a synthesis of all (except the NCAR) GS simulations available in the DDC in a 'T × P' (temperature × precipitation) diagram for the next century. The mean values for Poland are averaged for decades (decade numbers are on the diagram). The historical decadal values for the period 1951–1990 (observations) and 1960–1989 (re-analyses) are the reference points, plotted on the diagram as crosses. Under this comparison the GS projections for the region of Poland from the CCCM, JCCSR and CSIRO models are most different from observations. This depends on the season, however. The smallest changes in temperature and precipitation in comparison to observations are those projected by the two British models, particularly the HadCM2 model. There is a general trend entailing a shift in simulated climate towards increased precipitation. In the case of temperature a well-marked warming can be seen if the last decades of simulations are considered.

CONCLUSIONS

Simulations of the climate system by tray of ocean and atmosphere general circulation models are being made using the most powerful computers at many centres. The very important task is to monitor the development of new models and analyse the results of the latest computations. This paper sets out such an analysis for Poland and Central Europe. Our results indicate the great complexity of the problem. The presented climate scenarios differ, but can be considered certain possible realisations of the climate system. The above analyses are based on spatial averages in the region covering Poland and it is therefore impossible to infer any details concerning the spatial distribution of air temperature and precipitation fields within the region. Further investigations as to the interpretation of the results of general circulation models for the Central European area and Poland are ongoing at the Institute of Geophysics of the Polish Academy of Sciences.

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THE ROLE OF FOREST ECOSYSTEMS AND WOOD IN CONTROLLING THE ABSORPTION AND EMISSION OF CARBON DIOXIDE

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ABSTRACT: Forests play a quadruple role in the processes of global change: (1) as a cause, i.e. a source of the emission of greenhouse gases (GHG), predominantly in result of deforestation; (2) as a "victim" of global climatic change, due to the increased sensitivity of trees to pests and diseases; (3) as a beneficiary of global changes thanks to the "fertiliser effect"; (4) as a" remedy" for global changes thanks to their ability to sequester carbon.

The role of forests depends thus on methods of management and the ways in which forest products are used. Proper forest management can improve carbon accumulation through forest stand reconstruction, tending of forests, introduction of second layer and understorey, increasing organic matter, resignation of clear-cutting, elimination of intensive soil preparation. The basic method of improving carbon balance in land ecosystems is change in land use, above all via afforestation. The paper discusses the effects of forestry operations dealing with carbon accumulation in the forest ecosystems.

As equally important mechanism for improving carbon content in the atmosphere the author presents the repetitious recycling of timber production and its substitution in regard to materials and products requiring high amounts of energy input for manufacturing and utilisation (plastic, steel, aluminum, cement, bricks etc.) along with fossil sources of energy (timber combustion is neutral as far as emission of CO_2 is concerned). Resignation from fossil energy sources, using the biomass energy and retention of carbon by the proper forestry management offers a chance to attain the planet Earth atmosphere according to the level existing before industrial revolution – within some 100 years to come. The Kyoto Protocol may help to improve the balance. The Protocol, actually a politico-economic inter-governmental agreement, is reviewed in the paper on the background of the Polish forest economy.

KEY WORDS: forest management, climate change, carbon sequestration, wood utilisation.

INTRODUCTION

There is now an extensive literature anticipating far-reaching changes to the structure and functions of forest ecosystems as a result of probable climatic changes (IPCC II 1992). These are to reflect disturbances to the directions and rates of succession, which, in relation to the ecophysiological sensitivity of tree species to “greenhouse conditions”, will shape forest ecosystems. Many of the generated models of change anticipate the disappearance of species and the curtailment of forest area, at least on the regional scale (Smith and Tirpak 1989; Houghton et al. 1996).

Models will always be a more or less effective approximation of reality. This time the simulated reality upon which climatic change would impact is **everything** that surrounds us, i.e. the entire set of objects and phenomena existing on planet Earth. There would thus seem to be a justifiable doubt as to the degree to which modelling of such a complicated **reality** can really take account of all the important variables, and the extent to which models of this kind can be useful at all (Loehle 1996). This is especially the case since the construction of models requires ecophysiological knowledge deriving in general from before the period of “global change”, while many researchers claim that the understanding of the biogeochemical global carbon cycle and disturbances resulting from human activity is affording more and more problems (Steffen 1999), requiring us to return to basic research in this field. This is all the more the case as the anthropogenic effect overlaps with natural climatic fluctuations also on the scale of centuries – the Little Ice Age of the 17th and 18th centuries, for example (Grove 1988), or the Mediaeval Warm Period (Keigwin 1996; Michel 1999). All of this constitutes a particular hindrance when it comes to the interpretation of data and the prediction of future phenomena.

In the case of forests, there is also a need to take account of the inertia of a system that comprises long-lived species with reactions that are by their very nature delayed, and capable of being caused by or ascribed to other factors. There may be results masking the cause-effect relationship. For the evolution of trees has allowed for the development of mechanisms sustaining a species through even major disturbances – at least if these are relatively short-lived and present from time to time only.

Of course, if we are dealing with the climatic change as described in the literature, then we do indeed face durable agents of change and not merely one-off impacts on the Earth’s ecosystems. The conviction that this is so has been enshrined by the increasing concentrations of so-called “greenhouse gases” in the atmosphere (Keeling et al. 1976; Bacastow and Keeling 1981; Neftel et al. 1985) – one of the most important, if not the most important, problems for the development of civilisation in the late 20th and early 21st centuries. The involvement of the governments of most countries in the implementation of the 1992 UN Framework Convention on Climate Change (UN FCC), and the Conference of the Parties’ adoption of the so-called Kyoto Protocol of 1997 have ensured the high political and economic ranking of the issue of climatic change. Both documents relate to forests and forestry management as: (1) a source of the crisis thanks to deforestation; and (2) an opportunity to reverse dangerous trends through the increased absorption of carbon by “Kyoto forests”.

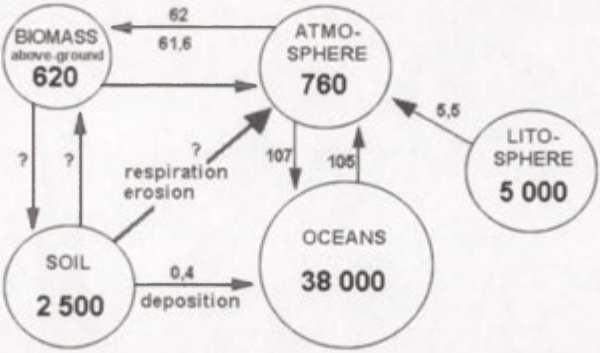

Figure 1. Main global pools of carbon and annual flows between them (in Pg); (after Lal 1999).

Those making an assessment of carbon in the Earth's ecosystems identify 5 main pools of the element (Fig. 1) (Lal 1999). These are:

- the oceans with 38,000 Pg of carbon;
- the lithosphere with 5000 Pg (including 4000 in hard coal, 500 in crude oil and 500 in natural gas);
- the soil, with 2500 Pg;
- the atmosphere, with 760 Pg;
- above-ground biomass, with 620 Pg.

The global streams of carbon flowing via the atmosphere, biosphere (vegetation) and hydrosphere (oceans) are huge in comparison with the c. 3.2 Pg-a year increase in atmospheric carbon (Lal 1999) that is now such a source of disquiet. Vegetation and the soil exchange c. 20 times as much carbon with the atmosphere as is emitted to the latter through the burning of fossil fuels. A limitation of increases in the concentration of carbon in the atmosphere would thus require small changes to this massive stream. At this point the attention is drawn to those areas to which humankind has operational access and hence an opportunity to intervene. From this point of view, the greatest possibilities for exerting an active impact concern the pool of carbon contained in above-ground biomass, as well as in the soil.

CARBON AND FORESTS

In accordance with the FAO definition, "forests" comprise tree vegetation at least 7 m in height with crowns covering 10–20% of the area. Such a definition is complied with on some 3,459,000,000 ha, or 27% of the Earth's land area (1995). "Other wooded areas", i.e. those with shrubby or tree vegetation 0.5–7.0 m high and a crown cover of < 10–20% occupy a further 13% of the land area.

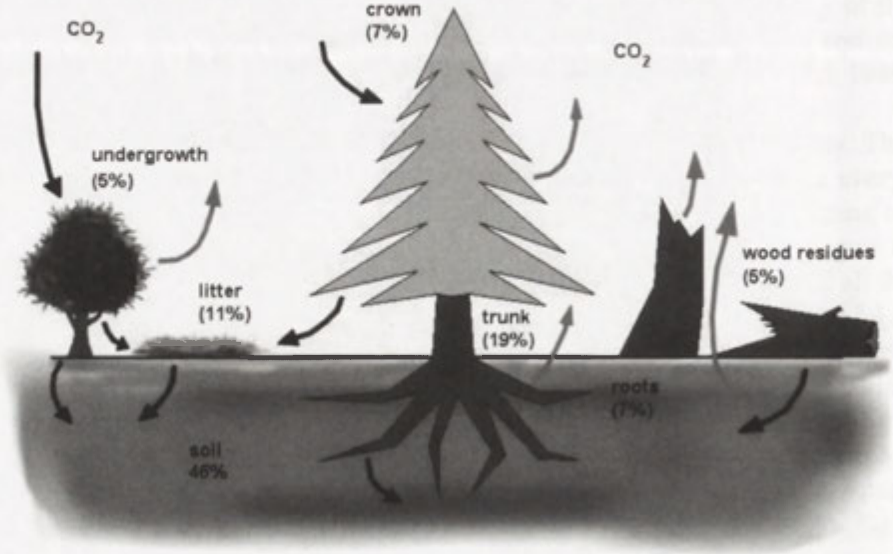

Figure 2. The carbon cycle in a tree stand (after Forestry Canada 1992).

Forest vegetation thus occupies a total of c. 40% of the land. More than half of this is in the Tropics (FAO 1995).

Like other plant communities, forests participate in the carbon balance by way of photosynthesis and respiration. They thereby serve as both places for the accumulation of carbon and sources of its emission. The global balance for these processes depends on the cycle of transformations, and especially on the fraction of carbon that becomes built into the organic matter produced in the form of:

- the assimilatory apparatus (crown) – c. 7.0% C;
- tree stems and trunks – c. 19.0% C (the trunk contains c. 66.0% of the whole tree's biomass, with 58.0% in timber and 8.0% in bark);
- stumps and roots – c. 7.0% C (c. 14.0% of tree biomass);
- timber residues – c. 5.0% C;
- litter – c. 11.0% C;
- organic matter in the soil – c. 46.0% C;
- the undergrowth – c. 5.0% C.

The anticipated climatic changes resulting from accumulating "greenhouse gases" in the atmosphere can give positive effects in the form of increased incremental growth: higher temperatures with increased precipitation and humidity may raise the productivity of forest ecosystems and the rate of regeneration (Kellomaki et al. 1988). On the basis of inventory data from 6 European countries in the years 1950–1980, Kauppi et al. (1992) stated that the last two

Table 1. Density of the carbon pool per unit area (t C/ha) in forests assessed in above-ground biomass and in the soil for different types of forest (by climatic zone) (after Dixon et al. 1994).

Country Continent	Density of carbon (t C/ha)	
	Above-ground biomass	Soil
Boreal forests		
Russian	83	281
Canada	28	484
USA Alaska	39	212
Mean	64 (15.7%)	343 (84.3%)
Temperate-zone forests		
USA	62	108
Europe	32	90
China	114	136
Australia	45	83
Mean	57 (37.0%)	96 (63.0%)
Tropical forests		
Asia – Pacific	132–174	139
Africa	99	120
South America	130	120
Mean	121 (49.6%)	123 (50.4%)
World	34.1%	65.9%

decades have seen an increase in net carbon uptake in European forests of between 85 and 120 × 10 6 tons annually.

The forests of the world are estimated to contain 80% of all the carbon accumulated on the land surface and c. 40% of that under it (in the soil, litter and roots). This gives nominal figures of 1146 Gt C (where 1 Gt = 10 9 tons). About 37% of this carbon is in tropical forests, 14% in those of the temperate zone and 49% in those of the boreal zone (Dixon et al. 1994).

Thus public opinion features what is in fact a myth concerning the role of the tropical forests as key areas for global change. The real picture to the significance of vegetational zones in shaping the climate shows that forests of the boreal and temperate zones are the key to regulating CO_2 in the atmosphere, and within them the amount of carbon in the soil in particular (Tab. 1). Forests of the Tropics are important in the context of the role of carbon in global change in that their cutting should be stopped as far as possible, or else new principles introduced for sustainable forestry. The densities of carbon in tropical forests are on average of 121 t C/ha in the above-ground pool (49.6%) and 123 t (50.4%) in the soil. The proportionality is reversed in forests of the temperate and boreal zones, where there is more carbon in the forest soil, respectively 96 t C/ha (63%) in those of the temperate zone and 343 t C/ha (84.3%) in boreal forests. The respective values for the above-ground pool are 57 t C/ha (37.0%) and 64 t C/ha (15.7%) (Apps et al. 1993; Dixon et al. 1994).

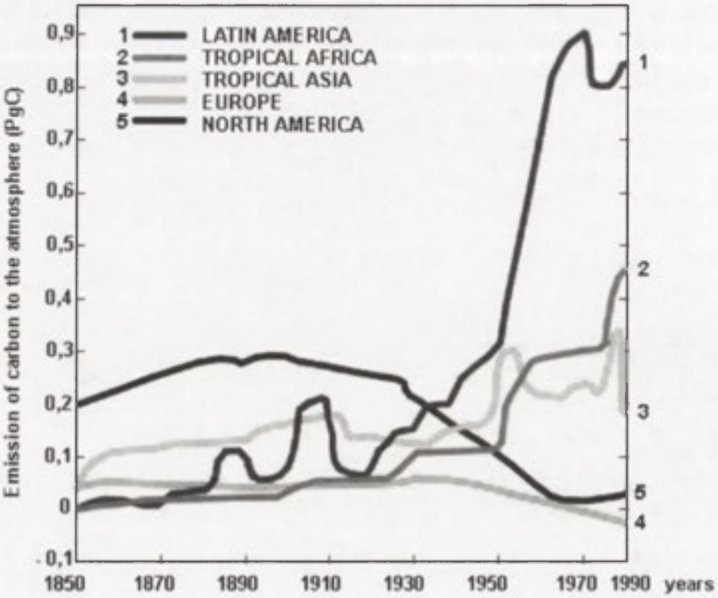

Figure 3. Annual (net) stream of carbon into the atmosphere by continent due to changes in land use (estimate after Houghton and Skole 1990; Houghton 1991).

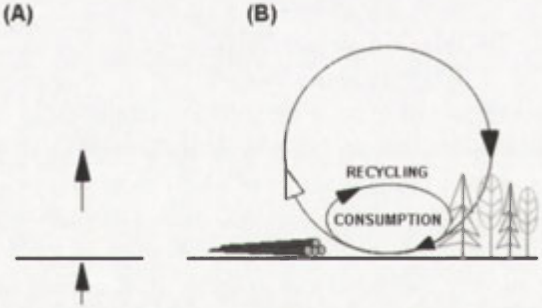

Figure 4. Stream of carbon to the atmosphere as a result of burning fossil fuels (A), as well as the closed cycling of carbon in the forestry sector (B).

Temperate-zone forests cover c. 600 million ha – or half the area that they could potentially occupy. The main locations are North America (c. 60%), Russia and Europe (c. 12% each). The remaining 16% of the total area is spread across Asia, Australia, New Zealand and South America. Poland makes a very small contribution here of 8,760,000 ha, or c. 0.002% of all forests and 1.4% of temperate-zone forests.

The basic mechanism changing the carbon balance in terrestrial ecosystems is a change in land use, mainly entailing changes in the areal share of forests

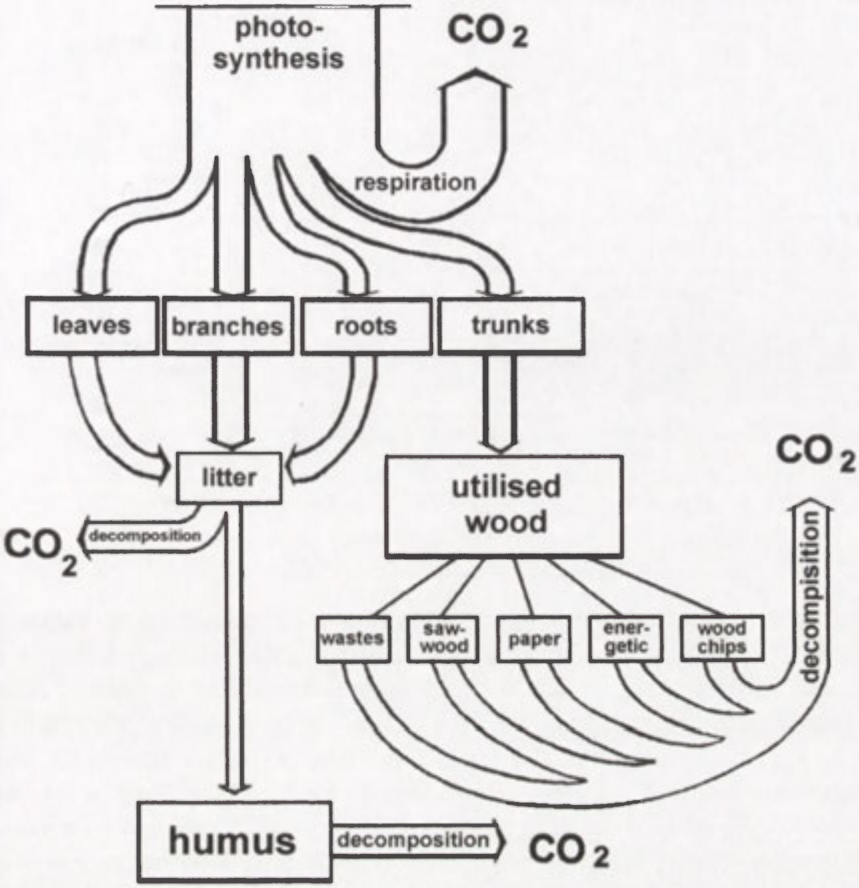

Figure 5. Schematic representation of the flow of carbon in a tree stand and utilisable wood.

within land cover (i.e. afforestation and deforestation) (Fig. 3). However, these are not the only areas of impact of forestry management on the pool of carbon in the atmosphere. Overall, the carbon content in forests is of a dual nature: (1) as the content in biomass, and (2) as a stream flowing through a forest ecosystem. The first static conceptualisation points to the opportunity for retention and serves the global balance, while the second speaks of operational possibilities and ways in which management can impact upon ongoing processes. Unlike the carbon contained in fossil energy sources, forest carbon participates in a closed cycle by which streams of carbon flow and may be used repeatedly through constant utilisation (Fig. 4).

The repeatability of the cycle of production of timber in forests and its direct or substitute utilisation provides an opportunity for the natural environment and forestry. Constant utilisation should in this case encompass not only forests, but also timber and its products (Fig. 5) (Hendrickson 1990).

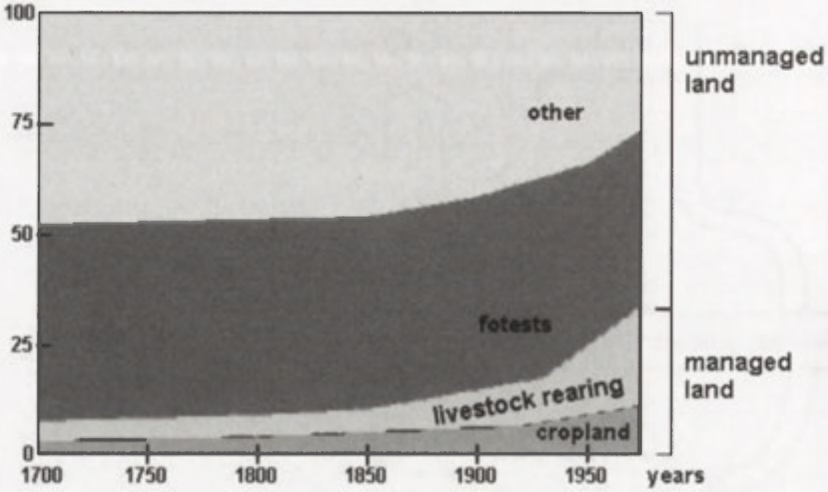

Figure 6. Changes in land use in the years 1700–1995
Dimensions and rates of deforestation (Klein Goldewijk et al. 1997).

As recently as at the beginning of this century, the rate of deforestation was still looked upon as a measure of progress (Fig. 6). The cutting of forests and associated burning to obtain land for cultivation is now the main cause of deforestation in tropical areas. An estimated 12–13 million ha of forest is cleared in this way each year (Calabri and Ciesla 1992). The consequent emissions to the atmosphere are of c. 1.6 ± 0.4 Gt of C (Dixon et al. 1994). Similarly, the vegetation of the African savannah is burnt at the rate of c. 750 million ha a year, in order that the fertility might be raised and the grass provoked into regenerating.

Carbon sequestration in the Tropics is more rapid than that in the temperate zone thanks to climatic conditions favourable to biological production in general (humidity and temperature). However, the true rate of sequestration of carbon (through incremental growth) is much lower in the Tropics than in other climatic zones, as wood there is mainly used as a fuel. It is estimated that 78.2% of the wood produced in tropical countries is burnt, while only 21.8% is used industrially (FAO 1982). In turn, energy from the burning of wood accounts for 17% of demand in tropical countries (as opposed to less than 1% in the developed countries (together with the former USSR). Such is the scale of the transfer of carbon to the atmosphere from forest production. Even so, it is still preferable to use wood, rather than fossil fuels, as an energy source. Nevertheless, the aim of a strategy for climate protection is not merely to halt the increase in the concentration of carbon in the air, but in fact to reduce it. Active reduction is made possible by increased sequestration and the rational use of wood and timber.

Timber and wood products like buildings, paper and furniture retain carbon for longer periods rather than releasing it to the atmosphere immediately. However, the industry of this type has been developed in the industrialised regions of

Europe, the US and Scandinavia rather than in the Tropics. In the developed market economies, 93.82% of the annual timber output serves as a raw material for industry and only 6.18% as fuel (FAO 1982). At present, tropical regions (of Asia, the Pacific, South America and Africa) are mainly importers of timber products and exporters of timber as a raw material. The demand for wood products will however increase, and for many reasons. Industrial plantations of trees in the Tropics might therefore constitute an economic boost to the development of developing countries, thereby leading to a reduction of the concentration of CO_2 in the atmosphere.

Discussion of the strategy by which to limit concentrations of carbon in the atmosphere has indicated the following categories of activity (Mathur and Bhandari 1993):

- the economical use of available energy and improvements therein (new combustion technologies, advanced energy-saving industrial technologies);
- changes in the structure of fuel use in the direction of those with low carbon contents, as well as renewables;
- increased sequestration of carbon through afforestation and improved forestry management.

The first two categories of action depend on the level of economic development of the country, as well as its political and social situation, while the third is independent of them and also connected with the possibility of resolving certain problems in other spheres of the economy and the environment.

CARBON AND WOOD

On average, wood is 48% carbon, mainly in the forms of lignin and cellulose. The retention of 1 ton of carbon from the atmosphere requires the production of c. 2.2 ton of wood (Chaturvedi 1994a; Dabas and Bhatia 1996).

The ability of forest trees to absorb carbon depends on:

- the growth possibilities,
- age (period of rotation),
- the durability of the product.

The rate of sequestration depends on the age of the tree (Fig. 7); in the period of physical old age, in later stages of succession, the balance may come to equal 0 thanks to the increasing breakdown of organic matter in the ecosystem. However, mature, ecologically "stable" forests may even come to act as a source of CO_2, thanks to disease, the death of elements of the flora and fauna and fires (Kyrklund 1990). Differences in increments in the mass of timber in different ecological and geographical conditions are presented in Table 2.

The management of forests with a view to maximising growth is at the same

Table 2. Incremental growth of timber in managed forests and plantations of some countries and climatic regions (after Evans 1982) as well as in Poland.

Country/region	Rotation period	Increment $m^3/ha^{-1}/y$
Canada (mean)	–	1.0
Siberia (Russia)	–	1.0 – 1.4
Sweden (mean)	60–100	3.3
US (mean)	–	2.6
UK (mean)	40–65	10.0
New Zealand (*Pinus radiata*)	20–40	18–30
South Africa (*Pinus* sp.)	20–35	10–25
Sub-tropical eucalyptus plantations	8–25	5–30
Tropical eucalyptus plantations	7–20	to 60
Tall tropical forest – managed	–	0.5–7.0
Managed forests of SE Asia	–	to 17.0
Poland (mean)	80–120	3.54

time management working to ameliorate the greenhouse effect, though the full environmental effect may be found unacceptable from the point of view of other forest functions.

c. 20% of temperate-zone forests are regarded as being managed, i.e. renewed regularly in the process of utilisation (Allan and Lanly 1991). The greatest potential for afforestation is in the temperate zone-although the final area suitable for reafforestation has not yet been established (Health et al. 1993) (Tab. 3). The figures may be c. 44 million ha in Europe and c. 100 million ha in the USA.

The accumulation of carbon begins with the establishment of a tree stand and the incremental growth of living biomass. The rate of growth is obviously de-

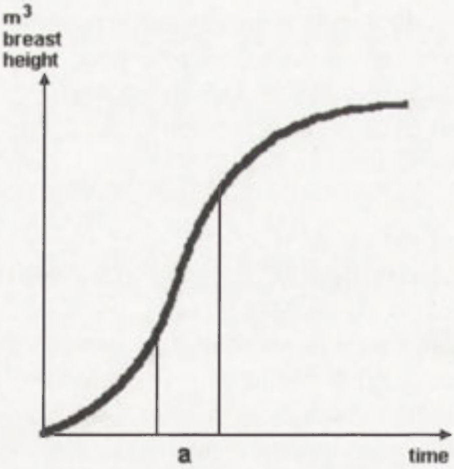

Figure 7. Growth curve for a tree.
a – period of intensive growth and enhanced retention of carbon.

Table 3. Potential area of land for reafforestation according to different authors (after Hall and House 1994).

Author	Total area in M ha	Comments
Grainger (1988)	758	From the 2007 M ha of degraded land in the Tropics, reafforestation should take in: 137M ha of utilised forests that should be managed naturally, 203 M ha of:" fallowed" (unrenewed) forest, 87 M ha of deforested catchment area and 331 M ha of land with advanced desrtification. These estimates derive from satellite imagery, such that some area may already be in use.
Myers (1989)	300	200 M ha require afforestation for reasons other than the greenhouse effect. 160 M ha of this is lowland in drainage basins which urgently needs reafforesting, other areas should be productive forest.
Dixon et al. (1991)	620–2000	This is the area which is accessible for reafforestation from the technical point of view, with not attention being paid to other possible limitations.
Alpert et al. (1992)	952	Area estimated as total available for the cultivation of halophytes; 125M ha is accessible thanks to restrictions due to the melioration of salinified land.
Houghton (1990)	865	Deforested and unused land in Asia (100 M ha), Latin America (100 M ha) and Africa (300 M ha). The remaining 365 M ha is the equivalent of 95% of the land once designated for agricultural ultivation and requiring reafforestation.
Beklering (1992)	553	Area of land theoretically accessible for reafforestation in 11 tropical countries following the satisfaction of agricultural needs; 385 M ha shouls serve in climate protection, 168 M ha available as "wasteland". Some land in this category may be in use already as pastureland.
Nilsson (1992) [in:] Nakicenovic et al. (1993)	265	A further 84.5M ha is available for agroforestry.
Trexer (1993)	67	This is the area considered realistic for conversion into forestry plantations in the next 60 years and still be economically sensible in view of the future trends in forestry policy, infrastructural development and other limitations.
POLAND (1997) National Policy on Forests, National Programme for the Augmentation of Forest Cover	0.7–1.5	The National Policy on Forests anticipates an increase in forest cover to 30% by 2020 and 33% by 2050. Reafforestation as well as the sustainable management of forests will allow for increased fixing and accumulation of CO2 by about 10% (i.e. 4.5 M tonnes) by 2020 and 20% (9.0 million tonnes) by 2050. The rate of afforestation will be made dependent on the availability of land and sources of funding.

pendent on climate (temperature and precipitation), habitat conditions and growth conditions (slope, exposure, soil texture, fertility, etc.) and the species and genetic structure of the tree(s) involved.

The most widespread methods of inventory make use of measurements of the commercial production of timber (in Poland merchantable timber), rather than biomass or carbon content. The basis for the inventory is measurement of the trunk in the living state. The use of a coefficient converting girth into biomass also allows for calculation of carbon content, although it is associated with errors and leaves gaps in accounting. The size of the latter depends greatly on the definition of many concepts and scenarios. It is certainly an undertaking of limited practicality to measure all the small trees which should be included within the pool of biomass.

Requirements under the Kyoto Protocol may be met through different countries' commencement of expanded routine inventorying so as to calculate biomass as well as commercial timber. This should entail the measurement and counting of small trees of non-merchantable timber and non-commercial timber on commercial trees (branches and roots). An inventory directed towards biomass is also required by the obligation under the Climate Convention that countries draw up reports of their output of greenhouse gases.

WOOD AS A SUBSTITUTE

The fact that a large amount of time elapses between the assimilatory removal of carbon from the atmosphere via biosynthesis in trees and the re-emission of that carbon in the course of decomposition ensures that the production of wood may be treated as a means of relatively permanent removal of the element from the atmosphere. This is well illustrated by the production of wood in spruce stands assuming a mean period for the use of the wood and its products and an average rate of decomposition (Fig. 8).

The pool of carbon contained in non-utilised mature forests is obviously larger than that in young ones renewed through the use cycle. Utilisation leads to the emission of carbon to the atmosphere. However, over short periods of time – as a result of the increase in productivity of young forests – there is an increase in the stream of carbon flowing from the atmosphere into the biomass produced. In addition, the products of wood and paper generally last longer than their natural source, i.e. wood (which decomposes relatively quickly in the forest environment). The basic principles of the strategy should therefore entail the location of wood in the most durable possible products.

An important element of sustainable forestry should be the substitute energetic value of wood, which may take the place of fossil fuels (Hendrickson 1990).

The incorporation of carbon into timber may be a promising mechanism in forestry and wood policy, especially because some species of tree grow quickly

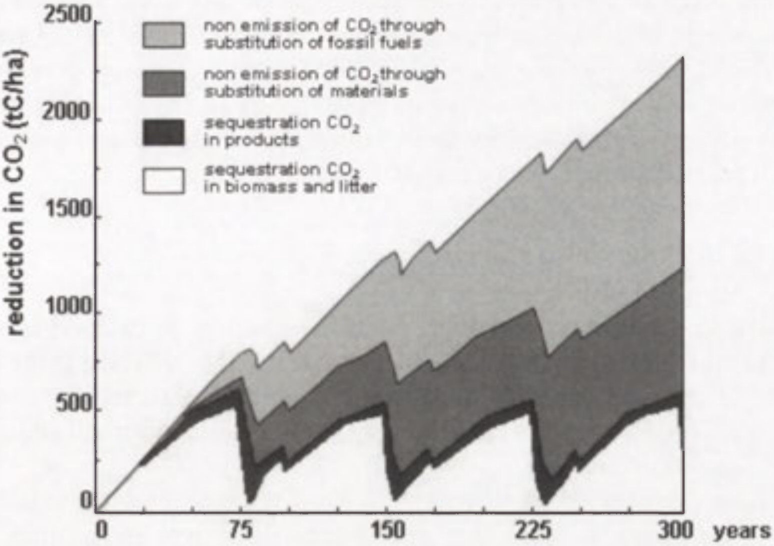

Figure 8. Overall effect in reducing CO_2 emissions of a spruce stand with a 75-year rotation cycle.

in conditions of an enhanced concentration of CO_2 and the greenhouse effect. European forests contain 2.8 Gt of carbon in the litter and between 3 and 4 Gt in soils. For comparison, 2.8 Gt of C is the amount emitted by the burning of fossil fuels in EU countries over about 4 years (Cannell et al. 1992). This carbon constitutes a relatively small portion of that contained in the forests of the temperate zone – 200 to 250 Gt.

The use of forest as a means of sequestering carbon is widely discussed. The matters of the small amount and low rate of assimilation are raised. It is, for example, estimated that the annual sequestration of carbon in forests is of c. 85–120 Mt (Kauppi et al. 1992), i.e. only 5% of emissions. For this to improve there would need to be a great many plantations of fast-growing trees established, with all the negative effects on the landscape and biological diversity that this is likely to entail. In addition, it needs always to be recalled that what constitutes a place of carbon fixation today may become an emission source in the future. About 1/3 of the carbon contained in timber as a raw material is almost immediately released in the course of processing and the production of wood products. After 50–100 years, wood has only 33–40% of its original carbon (as calculated for the raw material).

Wood participates in two ways in the reduction of the greenhouse effect:

- through the substitution of materials and products whose production and use is highly energy-intensive (plastic, steel, aluminium, cement, brick, etc.);
- through the substitution of fossil energy sources (the burning of wood is neutral from the point of view of CO_2 emissions).

A good illustration of the value of wood as a substitute is obtained by comparing the energetic and polluting potential of wood and steel in the building of a wall 3 m high and 30 m long of the same thickness (Meil 1995). Using steel requires 3.5 times more energy, with 3 times more CO_2 being generated and vastly larger amounts of other gases. The use of wood reduces the greenhouse impact by about 2/3, while only one-twentieth as much water is used and the pollution emitted into it is several tens of times more limited.

CARBON IN THE SOIL

If the main mechanism disturbing the carbon balance in the landscape is the change in the form of land use, then this is most strongly reflected in the content of carbon in the soil. Deforestation, disturbance of the soil surface by ploughing, degradation of the soil and reduced fertility – all result in increased emissions of carbon to the atmosphere.

The carbon content of a soil begins to come into existence with the fall of new organic matter. Carbon accumulates as a function of the type and quantity of live, growing biomass, while the rate differs with the type of cultivation and history of the land. If this was previously managed (cultivated), then afforestation leads to a considerable increase in the rate of accumulation of carbon in soil (IPCC report 1992).

For decades, the transfer from forest to uncultivated meadow involves no major change in the carbon content of the soil (Bonde et al. 1992; Christopher et al. 1997). In addition, the trend to the accumulation of organic matter in soil may in some cases depend strongly on the dimensions and rates of decomposition before and after the change in the form of cultivation. A degraded landscape and vegetation is characterised by a reduced amount of organic matter in the soil.

Changes in the carbon content in deforested areas also depend greatly on the type of use that ensues after deforestation. If the land is designated for agricultural cultivation the loss may reach 50% of the original amount (Mann 1986), though the losses are not so obvious if the land is used as uncultivated meadow.

The renewal of forest does not always lead to an increase in the carbon content from the very beginning. There may be cases in which the stand is felled and the renewal only takes place after several years during which the land is used in various ways and is a source of emission thanks to the decay of organic matter in the soil and the residue left after felling.

With reafforestation and renewal, the amount of carbon in litter and wood remnants (dead organic matter) increases over time. Deforestation is generally associated with the production of many wood fragments left over from felling. These may be limited by burning or carriage beyond the forest, but their role may also be very significant if everything remains in situ. The amounts of litter and wood residues are usually greater in natural unmanaged forests than in plantations.

Soils previously cultivated that are subject to reafforestation see an increase in the organic-matter content of the soil over tens of years or even centuries (O'Connell and Sankaran 1997). Soil organic matter declines rapidly in quantity at the moment of deforestation if this is followed by cultivation of the ground.

It needs to be noted that the soil contains about 3.3 times as much carbon as the atmosphere, and about 4 times as much as is in above-ground biomass (Fig. 1). The carbon contained in living residues and thin roots in forest ecosystems may represent 10–40% of that present in above-ground biomass. In mature ecosystems, a majority of soil carbon is in residues of dying roots; carbon in thin shortlived roots takes a majority part in the cycling of carbon within the ecosystem (Vogt et al. 1986; Nedelhoffer and Raich 1992). For allometric purposes, the amount of biomass in roots is correlated with the dimensions of trunks. The carbon content in soil is usually reported to be very variable (Ellert and Bettany 1995; Ellert and Gregorich 1996), something which limits its use to assessments in different local cases, global indexes or randomly computer-selected ones. In the face of the need to report on activities seeking to limit emissions of greenhouse gases – as required under the Kyoto Protocol – there is an urgent need for more precise data on carbon contents in the soil and methods of monitoring this pool.

The carbon content of litter, soil or wood residues may be easy, if quite costly, to determine in the course of field inventories, but it is almost impossible with the aid of teledetection. The use of simple models linking the carbon content below ground with certain features of a stand and its management/disturbance history is possible, but the reliability of such data is low if the model extrapolates from one set of ecological conditions to another, or from one geographical region to another.

The carbon accumulated in the upper layers of the soil is the most active pool and the one most sensitive to any kind of change, e.g. in land use or cultivation measures (Detwiler 1986). There are considerable opportunities for the sequestration of carbon in the soils of terrestrial ecosystems to be enhanced. The potential may be of up to 50–75% of the historical carbon content (in the whole period). In some specific soil conditions, the sequestration potential may be greater than the content in natural conditions or undisturbed ecosystems. For example, in the conditions of acid soils, ecosystems are limited by the high concentrations of toxic aluminium ions, and by a deficit of phosphorus. The removal or alleviation of these limitations may thus bring about the accumulation of organic carbon to a level exceeding that in natural conditions.

The restoration of fertility to a soil may thus be associated with increased sequestration of carbon. In theory at least, the annual increase in atmospheric CO_2 can be entirely offset by the restoration of 2 billion ha of degraded land that would increase the mean content of C to 1.5 MgC/ha in soil and above-ground biomass. In this event, the strategy for increasing the amount of carbon should take account of: (1) the increased saturation of the soil by carbon; (2) the reduced rate of decomposition; (3) the introduction of carbon into deeper parts of the soil profile. In addition, the increased accumulation of carbon in soils may arise through the use of plants with a high lignin content, and hence slow rates of decomposition. The plants in question are of course trees and shrubs, rather than "conventional" crops or grass.

THE UNINTENDED EFFECT OF AFFORESTATION

The least-known sink of carbon in the forest ecosystem is the soil. Many models simulating the accumulation of carbon in forests recommend the random selection of values for this (IPCC model), in the absence of more precise data. However, in the face of the high share of Polish stands that have been established through the reafforestation of former agricultural land (some 1.2 million ha), and the fact that this is planned to develop further via the National Programme for the Augmentation of Forest Cover (assuming reafforestation of 700,000 to 1 million ha), there is obviously a need to learn far more about the quantities and rates of carbon accumulation in ex-agricultural soils that are designated for reafforestation or have already been reafforested.

The Department of Ecology and Environmental Protection of the Forest Research Institute has undertaken research on this issue with reference to pine and spruce stands of the first generation following replanting on formerly agricultural land. The preliminary results obtained from 6 trial areas across Poland are suggesting that there are two different periods during which the carbon concentration in the soils of reafforested stands undergo development (Rykowski and Dovydenko 1999). These are: (1) the first period of 10–15 years from the moment the new planting takes place, during which carbon is released to the atmosphere, and (2) a second period of real accumulation, albeit with a marked slackening in the rate once stands are more than 50–60 years old (Fig. 9). If these results are supported by further analyses in further areas, then this will confirm that afforestation by way of the technologies applied hitherto may bring about a rise in emissions to the atmosphere, probably as a consequence of the method of cultivation entailing the ploughing of furrows. (It needs to be explained that the intensive methods of cultivation are as set out in "Silvicultural principles" for afforestation technologies in the 1960s and 1970s, raising the viability of cultivation, anticipating deep-ploughing, soil mellowing, hoeing, mechanical weeding, etc.). Preliminary calculations suggest that 1 ha of afforested land may release c. 1.3–1.8 tons of C annually in the first 10–15 years.

This result would seem to be in line with those obtained in the north-western USA (Harmon et al. 1990), where the felling of old stands and establishment of young plantations on 5 million ha led to the emission of between 1.5 and 1.8 × 10

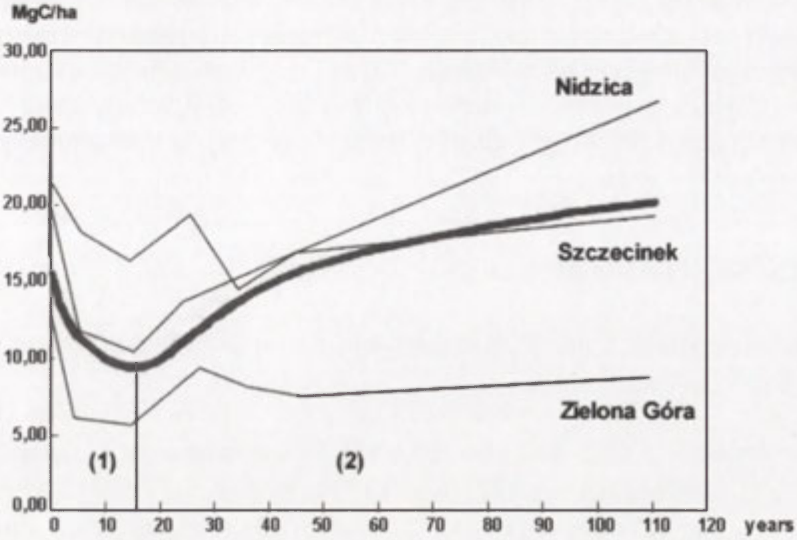

Figure 9. Development of the carbon content of ex-agricultural soils in relation to age of afforestation.

1 – period of decline in carbon content (emission),
2 – period of accumulation of carbon in soil (sequestration).

9 tons of carbon to the atmosphere over 100 years. This of course contributed to an increase in concentrations of the element in the atmosphere.

CARBON SEQUESTRATION AND NATURE CONSERVATION IN FORESTS

The Kyoto Protocol will exert a major influence on forestry policy in the next few years. The first results of the 1997 Conference of the Parties to the UN FCCC involved agreement as to the designation of money from industry and governments for the planting of trees and protection of forests (arborvitae 1998). The intention of these provisions has been to increase the rate of accumulation of carbon in forests and to reduce its influence on global warming. The money in question is to be used to implement projects of two kinds: Joint Implementation (JI) and the Clean Development Mechanism (CDM). Both are designated for developing countries. Unfortunately there is now a real danger taking shape in the form of an additional, and this time international and environmentally-motivated, disposition to change existing natural forests into plantations. This would mean the endangerment of one element of nature conservation – biodiversity – for the sake of another threatened element – the climate. Such a conflict of activity may be read from the attempts to implement the two leading UN Conventions on Biological Diversity and Climate Change.

The obviously conflicting orders being handed down to forestry by different instruments of international law (the 10–20 relevant conventions and other regulations now in force) are what is behind the call for negotiations on a Convention on Forests which would entail the development of coherent, cohesive and legally-binding principles for the pursuit of sustainable forestry in the various types of forest around the world.

CONCLUSIONS AND REMARKS

Forests appear in four different roles when it comes to the processes underpinning global change:

- as a “cause”, i.e. a source of the emission of greenhouse gases (GHG), above all of CO_2 (but also methane), as a consequence of deforestation and improper management (a lack of renewal or else delayed renewal);
- as a “victim” of global climatic change, thanks to the increased sensitivity of trees to pests and diseases, changes in the natural ranges of tree species and changes in species composition;
- as a “beneficiary” of global changes thanks to the “fertiliser effect” expressed through an increase in standing biomass and greater rates of growth;
- as a “remedy” for global changes, thanks to their ability to sequester carbon and to substitute other materials as well as fossil fuels.

The role actually played is thus dependent on methods of management and the ways in which forest products are used. Forests are the only instrument that can be applied on such a scale.

What strategy should be adopted to ensure that forests and forestry are used in the protection of the climate, and that Poland thereby meets its commitments under international law?

The European strategy for the participation of forests in the limitation of the greenhouse effect is contained within the concept for the sustainable management of forests. It pays heed to the Rio Forest Principles of 1992, as well as to the Helsinki Process (Resolutions H1 and H4). To this concept, it would be necessary to add measures for the durable long-term management (use) of wood and its products.

However, the situation in Europe is in fact far from being durable and sustainable. The role of forests in limiting the greenhouse effect varies from country to country, being most limited in The Netherlands, Belgium and the UK (c. 0.8% of national emissions of CO_2), and greatest in Sweden, where 88% of national emissions of this greenhouse gas are absorbed by the country’s forests). In Poland, the “forest compensation” for national emissions of CO_2 is at the level of c. 6%.

Observations of Europe's forests point to an increase in the standing crop and in the rate of increment of timber (Spiecker et al. 1996). This will mean the exhaustion of the retentive potential and reduced incremental growth within 50–100 years. Risks of an ecological and economic nature thus exist, if Europe's forests are permitted to grow at such a rate. New afforestation will not help, the main problem at present is how to use the existing forests and the wood they produce. It is possible to point to four means by which the objective could be attained, all of which would need to be applied simultaneously:

- approximation of the real utilisation of forests to the growth possibilities;
- substitution of non-renewable materials by renewable ones;
- recycling;
- the generation of energy from renewable sources.

Coming into focus against such a background is a developmental dilemma within the "economy-ecology-society" triangle, or, to put it another way, economic development, the state of the environment and nature conservation. The steps that would need to be taken include:

- an increase in harvests to levels permitted by the annual timber increment (harvesting has hitherto been at an average 65% of the level of increment in Europe);
- stand renewal using fast-growing species (like Douglas fir);
- the reafforestation (by plantations) of formerly agricultural land;
- enhanced recycling of wood products;
- an extension of the useful working lives of wood products;
- a reduction in emissions from fossil fuels through the use of wood in producing energy;
- enhanced retention of carbon in soils.

The fact that this is possible is attested to by the mechanism for the reduction of CO_2 in the atmosphere that results from the appropriate management of a spruce stand and proper utilisation of the wood produced (Fig. 8). The attention is in particular drawn to the increasing effect of the accumulation of carbon in products whose durability period exceeds the rotation in timber production (length of time between cuts).

Can a similar strategy be foreseen for Poland?

On the basis of statistical data for timber production, and taking account of fires and afforestation, the content of carbon in Polish forests (tree biomass) in the years 1988–1990 was of between 20.2 and 22.7 million tons of CO_2. According to other sources (Bernadzki 1993), Polish forests contain 45–50 tons of accumulated C per ha.

There are many forestry operations that may improve the retention of carbon in Polish forests:

(1) the reconstruction of stands (by which 20–25 t C/ha may be obtained);

(2) improvement cutting – the effect from increased illumination;

(3) the introduction of a second layer of vegetation (e. g. a second layer of beech in pine stands may increase the retention of carbon by 0.4 t C/ha;

(4) increasing the organic mass in the soil and improving humus management (clear cutting is expressed in a loss of c. 15 t C/ha);

(5) afforestation (c. 80 t C/ha in a 60-year-old stand on ex-agricultural land)

Bearing in mind the possible dimension of the aforementioned forestry operations, forestry may increase the retention of carbon in Polish forests:

- by 200–215 million t C as a result of stand reconstruction;
- by 16–20 million t C as a result of the second layer and understorey;
- by 80–240 million t C as a result of new afforestation.

The issues of global change and emissions, as well as the sequestration of carbon, have become a political problem first and foremost. When it became apparent that the assumed reductions in emissions in line with the Kyoto Protocol bring increased unemployment and redundancies among more than 1.6 million people in developed countries, the information on the real levels of the emission or retention of carbon ceased to be unambiguous. Government control over the release of data can be seen clearly. For there is an impact on internal development strategies – meeting of the obligations under international law may hold up economic development. So the information that is appearing is conflicting, imprecise, sectoral and hard to interpret.

Land use remains one of the main political instruments through which the Kyoto obligations can be complied with. Scenarios for land use over the whole globe point irrevocably to the key role of forests and forestry (Fig. 10). The only chance for the atmosphere to return to its original pre-industrial state after 100

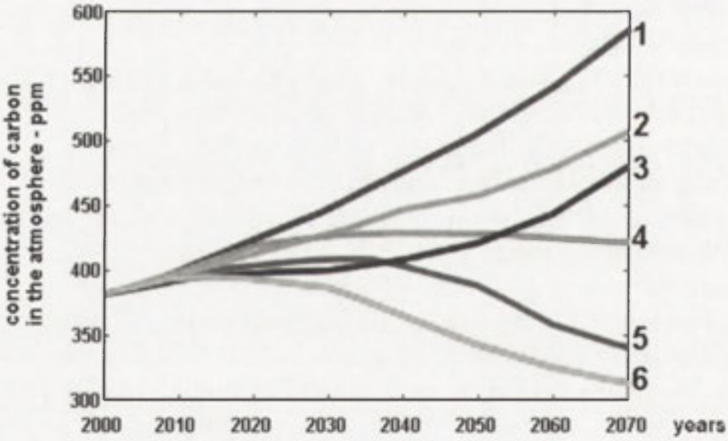

Figure 10. Simulation of CO_2 concentration in the atmosphere (ppm) according to different land-use scenarios (after Read 1997).

1 – unchanged land use, 2 – unchanged land use + energy from biomass, 3 – unchanged land use + energy from biomass + forestry, 4 – energy from non-fossil sources, 5 – energy from non-fossil sources + energy from biomass, 6 – energy from non-fossil sources + energy from biomass + forestry.

years or so may be provided by simultaneous use of a combination of three activities simultaneously, i. e. resignation from fossil fuels, the use of energy from biomass and the retention of carbon via forestry management.

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CLIMATIC AND OCEANOGRAPHIC CONDITIONS IN THE SOUTHERN BALTIC AREA UNDER AN INCREASING CO_2 CONCENTRATION

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ABSTRACT: The large-scale atmospheric sea-level pressure field over Europe and the North Atlantic has been downscaled by means of canonical analysis or redundancy analysis to some local climatic and oceanographic fields on the Polish coast of the Baltic Sea. These local fields are: wind at coastal stations; the wave field on the southern Baltic; air temperature on the coast; and salinity in the coastal zone. Scenarios concerning the future evolution of the local systems have been developed using results of some numerical experiments with GCMs, e.g. ECHAM1/LSG *transient*, ECHAM3 *time-slice* and ECHAM4/OPYC3 *transient*. Some significant changes should be expected, e. g. a continuation of the presently-observed rise in sea level with its alternation when the CO_2 concentration triples, a slow increase in mean windspeed (especially in its zonal components), an increase in windspeed variability, an increase in the range of variability in wave height, a continuation of the observed trend for air temperature with alternation of this process during winter and a slow decrease of salinity in the coastal zone and open sea.

KEY WORDS: statistical downscaling, climatic scenario, sea level, wave height, wind, air temperature, salinity, Baltic Sea, Polish coast.

INTRODUCTION

Water vapour (H_2O), carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4) and ozone (O_3) are among the main greenhouse gases in the atmosphere (IPCC 1990). It is estimated that, in comparison with the pre-industrial state (c. 1750), concentrations of CO_2 have risen by 30%, those of methane by 145% and those of N_2O by 15% (1992 data). This has resulted in a positive disturbance of the energetic balance of the Earth-atmosphere system of the order of 2.45 Wm^{-2}. The most significant changes are associated with the increasing concentrations of CO_2 (1.56 Wm^{-2}). CO_2 and N_2O may disrupt the energetic balance of the system for many years, because they are characterised by relatively long life times in the atmosphere, estimated at many decades or even centuries. CFCs are responsible for a change of the order of +0.25 Wm^{-2}, but since they are also responsible for depletion of stratospheric ozone allowing for the release of heat, their ultimate influence is smaller by $0.1 Wm^{-2}$. Certainty as to the role of the aforementioned gases in shaping the energetic balance of our planet is extraordinarily high, while the role and influence of other greenhouse gases and aerosols is much less well-known, with all numerical data still remaining highly unreliable (IPCC 1994). For this reason, CO_2 may at present be regarded as the most important greenhouse gas present in the atmosphere, and thus the greatest threat to the planet's climatic system.

In the view of the IPCC (1990, 1995), positive distortion of the Earth-atmosphere energy balance is the main cause of the process of global warming, as a result of which:

- the mean air temperature of the globe has risen by between 0.3 and 0.6°C since 1860, and is likely to rise by a further 1.0 to 3.5°C up to the year 2100 (depending on the emissions strategy adopted in the meantime);
- mean sea level has risen by between 10 and 25 cm in the last 150 years, and will continue to rise by between 15 and 95 cm in the period to 2100, again in relation to the emissions strategy adopted.

To date, the IPCC assessments of the future evolution of the Earth's climate have referred to the global situation, saying virtually nothing about regional changes, and nothing at all about local aspects. This is a rather major disadvantage, particularly since all programmes for adaptation to changed climatic conditions must relate to particular areas.

STATISTICAL DOWNSCALING

Global models of the general atmospheric and oceanic circulation are describing the Earth's climate more and more reliably. However, on account of their relatively limited resolution (reaching T106 at present), they are not able to reflect adequately the influence of, for example, topography (changes in shorelines, mountain chains) on the continental scale.

Downscaling is based on the view that local climate is defined by climate on the regional or even continental scales. Information is transferred "top-down" from the larger scale to the smaller. Regional climate is first and foremost the result of the impact of oceanic and atmospheric circulation with factors specific to the region like topography, the distribution of sea and land and forms of land use. However, the idea of downscaling does not denote that the local climate will be determined by the state of the larger-scale system, because similar states of the latter may be associated with climates on the local scale that differ markedly. This concept has direct application when it comes to global change, with the result that there has recently been much stress placed on the need to obtain more detailed information on the local scale – information that global circulation models (GCMs), the main tools in the detection of climatic change, the attribution of causes and the determination of future evolution of climate, are not in a position to supply. The conditioning as regards the use of global models in preparing scenarios for change on a smaller spatial scale has been discussed in great detail by Robocka et al. (1993). The techniques behind downscaling have in turn been discussed by Storch et al. (1997) and Zorita and Storch (1997).

Statistical downscaling is often based on the empirical transfer functions between the large-scale and local elements designated with the aid of such methods as principal components analysis (PCA, Preisendorfer 1988), redundancy analysis (RDA, Tyler 1982; Storch et al. 1997), canonical correlation analysis (CCA, Hotelling 1936; Barnett and Preisendorfer 1987) or singular values decomposition (SVD, Smithies 1970; Bretherton 1992). In most cases, the large-scale element is atmospheric pressure at sea level, on account of both the considerable role played by atmospheric circulation in shaping climatic conditions and the availability of daily reanalyses (NCEP/NCAR Boulder, USA) from the end of the 19th century onwards.

Local climatic and oceanographic conditions in the Southern Baltic area are described mainly by the wind at coastal stations, the level of the sea along the Polish coast, wave height, air temperature at coastal stations, the sea surface temperature (SST) and the salinity.

The future variability of the climatic conditions of the Southern Baltic has been presented on the basis of the results of numerical experiments carried out at DKRZ in Hamburg within the framework of the three global models ECHAM1/LSG, ECHAM3 and ECHAM4/OPYC3.

The first experiment, termed "pre-industrial", was conducted as part of incomplete coupling of atmosphere-ocean systems. The ECHAM1 atmospheric model is a spectral model with a resolution close to 5.6° × 5.6° (T21) and 19 levels. LSG is a large-scale geostrophic model of ocean circulation characterised by an effective resolution of c. 4.2° × 4.2° and 11 levels (Cubasch, Hasselmann et al. 1992). The (synchronic) coupling system between the atmospheric model and the oceanic leads to the correction of energy and mass fluxes with a view to limiting climate drift. The experiment in question assumes commencement in 1935 (here taken to be the beginning of the industrial era). The concentration of CO_2 up to 1985 changes in a realistic way (i.e. in line with the changes actually observed). From 1986 onwards, the concentration of CO_2 rises steadily through to the year 2090 in a manner according with the "business as usual" scenario (scenario A of the IPCC 1992), i.e. at a rate of c. 1.5% a year. As a result, the effective concentration of CO_2 is doubled by the year 2035. Forcing for the calculations was selected in relation to the mean values for the period 1961–1985.

The second experiment was carried out within the framework of ECHAM3 and termed "time-slice" (Cubasch, Waszkiewitz et al. 1995). The concentration of CO_2 is constant through the whole experiment and equal to the doubled concentration from the end of the 1980s. The boundary conditions are constant, while SST and ice cover data are taken to be the means for a period of ten years of the control course of ECHAM1/LSG (Voss at al. 1997). The resolution of the model is of the order 2.8° × 2.8°. There is full feedback between the atmosphere and the ocean. Forcing for calculations derived from the period between the 3rd and 34th years of the experiment and was selected in relation to the control course – an analogous simulation with a constant concentration of 1 × CO_2.

A further, third, experiment was run within the ECHAM4/OPYC3 framework. ECHAM4 is a spectral atmospheric model with a horizontal resolution of T42 and 19 vertical levels. On the other hand, OPYC3 is an oceanic model with a resolution according with an atmospheric model in the area of mid latitudes (with finer resolution in the tropics), and has 11 vertical levels (Roeckner, Bengtsson et al. 1998). In the experiment, the concentration of CO_2 in the period 1860–1990 changed in line with the conditions observed, while subsequent change was in accordance with scenario A (IPCC 1992).

The empirical transfer functions between the regional atmospheric pressure field over Europe and the North Atlantic and local climatic and oceanographic conditions in the Polish coastal area described mainly by the wind at coastal stations, sea level, wave height, air temperature, sea surface temperature (SST) and salinity (SSS) at coastal stations have been described in detail in Miętus (1999). The link between sea level pressure and the wave field on the Baltic Proper has been presented by Miętus and Storch (1997). The relations between atmospheric pressure and salinity and oxygen concentrations in the open sea area were discussed by Laine and Zorita (1999).

SCENARIOS OF THE VARIABILITY OF CLIMATIC AND OCEANOGRAPHIC CONDITIONS

THE WIND AT COASTAL STATIONS

The application of PCA methods allows for the identification of features characteristic of the regional pressure field and wind field at coastal stations. Decided dominants are the configurations presenting: (a) two large-scale pressure systems with centres localised over the Iceland and Azores areas (NAO, 24% of variance of the field in autumn, 29% of the variance of the field in winter), (b) two large-scale pressure centres of which the one encompassing the whole of the European continent has its centre in the Baltic area, while the other over the ocean has its centre over Greenland (18% of the variance of the field in summer, 21% in winter), (c) a large-scale system taking in almost all of the analysed region, with its centre in the area of Ireland (13% of the variance of the field in spring, 16% of the variance in winter).

The projections for changes in the wind field at coastal stations prepared on the basis of the *time-slice* experiment (ECHAM3) point to the possibility of the occurrence of a statistically non-significant increase in mean wind speed and a change in its mean direction. An important change in the case of a doubling of the CO_2 concentration as compared with that in the late 1980s is increased variability to both of the components, reaching ±6ms^{-1} in winter, with the possibility of winds exceeding long-term values by as much as 9–10 ms^{-1}. The result may be a quite marked change in the distribution of wind speed at stations on the Polish coast, as well as an increase in the frequency of occurrence of strong and very strong winds. In relation to the mean direction of the wind observed at present, it is possible that there will be an increase in the frequency of winds blowing from both the south and the north-west. This may denote an increased amount of water in the Baltic, greater inclination of its surface in a west-east direction and a rise in the height of peak storm water levels and in the range of variability to wave height (albeit with no major changes to mean heights).

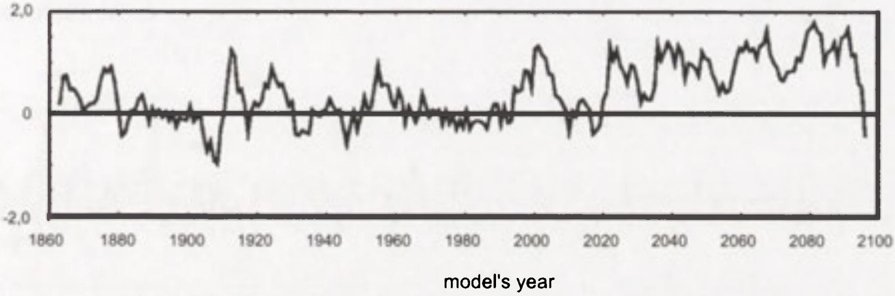

Figure 1. Relative intensity of the first eigenvector of the atmospheric pressure field over Europe and the North Atlantic in the winter period, according to ECHAM4/OPYC3 *transient*.

The quantitatively different results deriving from ECHAM4/OPYC3 reflect this model's prediction of a quite marked intensification of the westerly flow in the area of the North Atlantic and Europe in connection with an increased value for the NAO index (Fig. 1). This major intensification of westerly flow is anticipated for the late 2030s and early 2040s. The result in the case of the wind at both coastal stations and over the Baltic should be an increase in the mean value for the zonal component. At the same time, an increase in mean wind speed of c. 2 ms^{-1} is also expected. The same global experiment foresees a significant north-easterly shift in the path of cyclones of the north-eastern Atlantic and Europe. The effect of this change is likely to be an increase number of extra-tropical storms, whose trails will lead across the Baltic.

WAVE HEIGHT

The projections of results from the general circulation model in *time-slice* conditions do not point to any likely significant rise in wind speed or the height of wind waves or swells, though the expected quite significant increase in the degree of variability of these factors (by 1.5–2.5 m in the Baltic Proper) will probably bring an increase in the potential threat to the shoreline zone.

A consequence of the intensification of the NAO and Baltic-ward shift in the track of extra-tropical cyclones (ECHAM4/OPYC3) may be an increase in the mean height of wind waves and in the range of variability to it by values higher than those resulting from earlier simulations.

SEA LEVEL

Scenarios for future changes in sea level associated with anticipated changes in regional atmospheric circulation caused by increasing (doubling or tripling) CO_2 concentrations reveal both the character and size of the potential changes. The projections for local changes obtained from the results of global models of atmospheric and oceanic circulation have many common features, though they also differ.

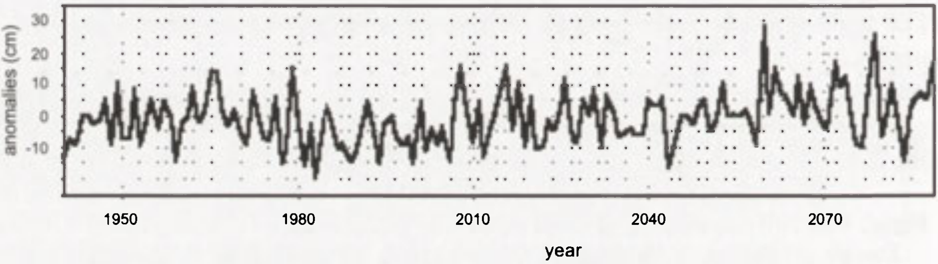

Figure 2. Variability of the 95% quantile for the maximal winter sea level at Władysławowo, according to ECHAM1/LSG.

This is a consequence of qualitatively significant differences appearing between the ECHAM1/LSG and ECHAM3 models. However, irrespective of the GCM, the local projections point to a several-centimetre rise in sea level in conditions of a concentration of CO_2 twice that in the late 1980s. They also indicate a considerable rise in the variability to both the mean and maximum levels, including the high-order quantile (Fig. 2). This may be a consequence of the increased number of storms in the Polish coastal area, or probably also of an increased volume of water in the Baltic due to circulational changes.

In the *time-slice* experiment for the gauges at the Vistula mouth, the scenario drawn up indicates the possibility of a decline in variability as compared with neighbouring gauges in both summer and spring (Fig. 3). Because the gauge in question is very much controlled by the flows of the Vistula at Tczew, this may attest to a decline in the flows of the Vistula along its lower course.

The scenario for the change in sea level along the Polish coast, being based on the ECHAM4/OPYC3 model, would seem to point to an intensification (as compared with the end of the 20th century) of the process of sea-level rise, as

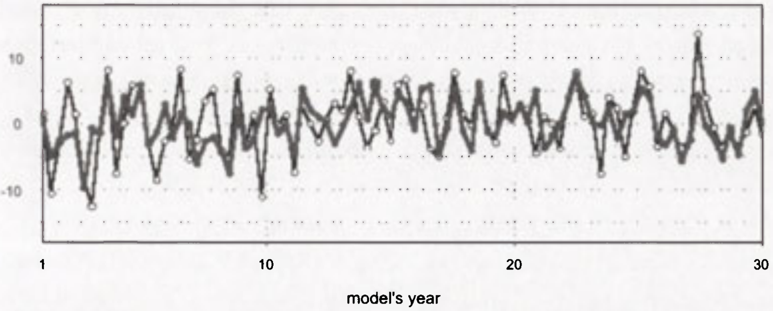

Figure 3. Variability to anomalies in the mean sea level at Gdańsk Port (black line with unfilled circles) and the Vistula Mouth (grey line), according to ECHAM3 *time-slice*.

well as to an increase in the frequency of occurrence of high-water states posing a significant threat to the coast.

AIR TEMPERATURE

Air temperature in the area of the coastal stations shows a close relationship with regional pressure systems encompassing a considerable fraction of Europe and the North Atlantic. In each of the four climatic seasons, and in the year as a whole, more than 90% of the variance in mean air temperature is explained by atmospheric circulation. The marked dominance of zonal circulation in forming thermal conditions is confirmed. Also revealed is the influence of the summer-warmed waters of the Baltic. The role of the deep-water basins of the Gulf of Gdańsk in shaping thermal conditions at coastal stations is particularly marked in autumn and winter.

The scenario for changes in thermal conditions devised within the ECHAM1/LSG framework shows a constant increase in air temperature. Variability to temperature is characterised by a multi-seasonal pseudo-oscillation. There are no sudden jumps in mean value associated with the increase in CO_2 concentration. Compared with the conditions holding sway in the period 1961–1980, those anticipated with the scenario devised on the basis of ECHAM3 results show an increase in the variability of air temperature, especially in the winter season. Mean values for the series of anomalies are positive, denoting a further acceleration of the rate of increase in air temperature in conditions of doubled CO_2 concentrations (an increase of 0.28°C over 30 years).

SEAWATER SALINITY

As is revealed by empirical transfer functions between the regional pressure field and the salinity of surface waters at the Polish coast, the influence of atmospheric circulation on changes in salinity is relatively limited (absolute values for the anomalies to the salinity field are low, basically not exceeding 0.3 PSU). At the same time, analysis shows the inadequacy of an explanation of the distribution of anomalies that assumes a simple relationship of *anomalies in the pressure field – wind forcing – movement of surface masses – influxes of water of differing salinity*. The interpretation of canonical maps requires a knowledge of:

- the distribution of currents in deeper layers of water,
- the existence in the given region of at least a seasonal vertical gradient to salinity (it is generally known that the surface waters of the Baltic feature a very weak vertical gradient of salinity to the halocline, which lies at different depths in different basins),
- the dynamic to the process of mixing of layers of water (including the influence of waviness and inflows of salty ocean waters),
- the influence of freezing,
- (above all) river flows into the Baltic, which play the greatest role in salinity variation on the seasonal and annual scales (Miętus 1999).

Analogous analysis carried out for areas of open sea shows a strong dependent relationship between atmospheric circulation and the salinity of the upper layer of seawater to a depth of 50 m, and of the deep layers more than 50 m below the surface. In both cases, the dominant mode of the pressure field is the North Atlantic Oscillation (Laine and Zorita 1999).

In connection with the anticipated rise in the intensity of westerly flow (ECHAM4/OPYC3), it is expected that there will be a decline in salinity in both the surface and deep-water layers of the Baltic Proper with the exception of south-western basins. This is a consequence of a very major rise in precipitation totals for Finland and Russia, and associated river inputs into the Gulf of Finland, as well as a considerable decline in the amount of precipitation in the basin of the Baltic Proper.

CONCLUSIONS

Changes in climatic and oceanographic conditions in the Southern Baltic region associated with a rise in the CO_2 concentration will proceed in a manner according with global changes. The dynamic to changes in features of the local climate and their magnitudes will however differ quite markedly from those typified for global processes. The scenarios for change in local conditions devised via the technique of statistical downscaling suggest that possible changes will ensue without dramatic change in mean values. The fundamental feature of future climatic and oceanographic conditions in the Southern Baltic area is the rise in the range of variability for particular elements. In the face of the anticipated further rises in sea level, wind speed and air temperature, as well as the range of variability to wind wave, in the Polish coastal region, it is possible that there will be an increased incidence of phenomena posing a threat to the shoreline zone. The expected fall in salinity of both surface and deeper layers of water may in turn be a harbinger of unfavourable ecological changes in the marine environment.

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SYNOPTIC – CLIMATIC STRUCTURE OF THE EXTREME AIR THERMAL PHENOMENA IN POLAND

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ABSTRACT: The influence of atmospheric circulation upon extreme temperatures in Poland is being analysed. Maximum and minimum temperature values have been collected from 19 meteorological (synoptic) stations for the period 1951–1999. Simultaneously, a catalogue of circulation types after Osuchowska-Klein has also been used. An analysis of mean monthly and seasonal values is provided, as well as the conditional probability of selected temperature thresholds during the occurrence of particular types. Days with maximum temperatures over 25°C, minimum temperatures below –15°C and the absolute extremes for the selected stations have been investigated in detail. This confirmed a significant influence of atmospheric circulation upon the occurrence of extreme temperatures much larger than other local factors. The last part contains an analysis of the number of days with given thermal characteristics with respect to circulation indices.

KEY WORDS: maximum and minimum temperature, extreme temperature values, atmospheric circulation, synoptic climatology.

INTRODUCTION

In the temperate zone air temperature is very much determined by circulation factors and therefore depends mainly on the direction and type of incoming air masses. The influence of atmospheric circulation on air temperature occurrences in Poland has already been confirmed by reference to different mean values (e.g. Osuchowska-Klein 1992; *Regionalne...* 1996). In the present study special attention has been paid to the role of circulation in the formation of extreme air temperature values. It is these, not different mean values that create a menace in specific economic types of activity and can cause damage in the entire natural environment.

MATERIALS AND METHODS

As was stated in the introductory chapter, the main objective of the study has been the quantitative estimation of the atmospheric circulation upon the formation of particular air temperatures, with special respect to extreme values. That relationship between circulation and air temperature was expressed by calculating mean daily maximum and minimum temperatures with particular circulation types, as well as by defining the frequency and conditional probability of days with specific extreme air temperature values. All these probabilities were calculated for particular circulation types. The characteristics mentioned above were calculated for a year, months, and particular seasons. The analysis was based on daily values originating from the period 1951–1999. Daily values for maximum and minimum air temperatures from the standard meteorological screen height of 2 m above ground level were used. Data were collected from 19 meteorological stations of the synoptic type and were therefore of high quality. Synoptic stations are the basis of the national meteorological network and are relatively evenly located across the whole territory of Poland. Data – monthly values – were additionally checked against inhomogeneity by applying the Alexandersson test. The study presents an example of the synoptic climatological approach (Yarnal 1993). The cause-and-effect relationship between circulation conditions and extreme air temperature is investigated. Circulation conditions in the main part have been defined using the Osuchowska-Klein classification of circulation types (1975), well known in the Polish literature. It was applied despite the fact that it provides wider air temperature dispersion with a particular circulation type than some other known classifications (*Ekstremalne...* 1997). At the same time the Osuchowska-Klein calendar creates relatively large statistical samples which can be calculated for each type. This is especially important for the monthly analysis where the numbers of particular circulation types are rather small.

The main phase of the study consists of probability calculations of the frequency of days with specific extreme air temperature thresholds given particular synoptic types. Such analysis is especially useful when one tries to estimate the menace to the forecast. The study presents the examples of the analysis for January and July only at 3 selected stations: Hel, Kraków (Cracow) and Warszawa (Warsaw), representing different geographical regions.

MEAN DAILY EXTREME VALUES OF AIR TEMPERATURE

In the first part mean daily values for extreme air temperatures during particular circulation types have been calculated. Figures 1–2 present the differentiation of minimum air temperature as deviations from the mean value in January and July, 2 months with the extreme thermal conditions. As can be observed, in spite of the quite different locations of all stations, deviations from the mean minimum air temperatures are quite similar. This confirms the dominant role of atmospheric circulation in the formation of thermal structure. It should be stressed that these dependent relationships are also quite well expressed in summer, when the radiative factor plays a more major role than in the winter season.

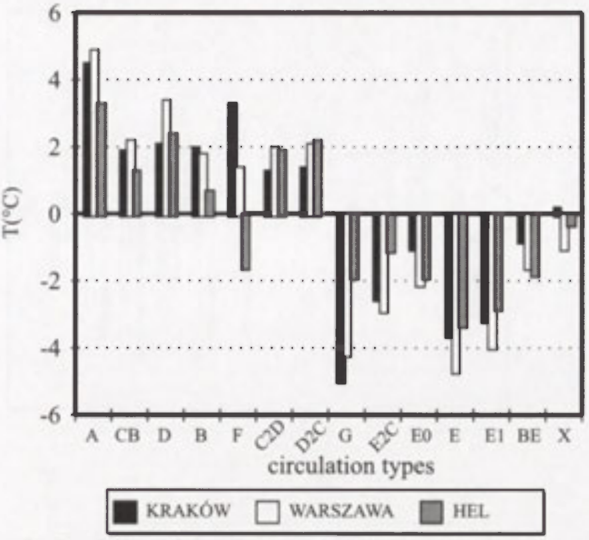

Figure 1. Deviations from the mean minimum air temperature (°C) under different circulation types – January.

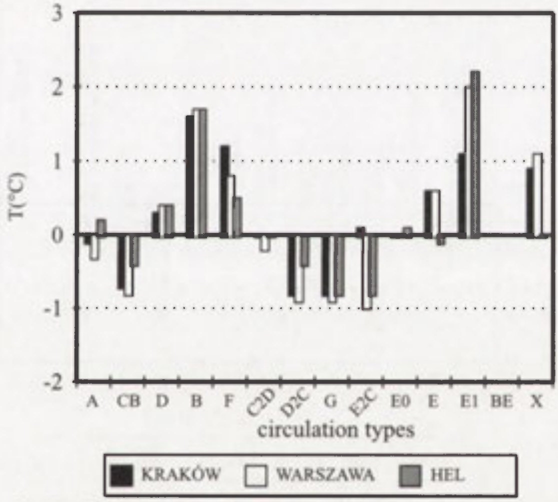

Figure 2. Deviations from the mean minimum air temperature (°C) under different circulation types – July.

Figure 3 confirms the positive influence of cyclonic westerly circulation types on the occurrence of maximum temperatures in January; something that has already been mentioned many times in the literature (Kuziemska 1987; Osuchowska-Klein 1992; *Ekstermalne*... 1997). In the presence of the cyclonic westerly circulation type (A) the positive deviations of maximum air temperature reach almost 5°C over most of the country. Air temperatures with the D (south-westernly cyclonic) and D2C (south-westernly and south anticyclonic) types are

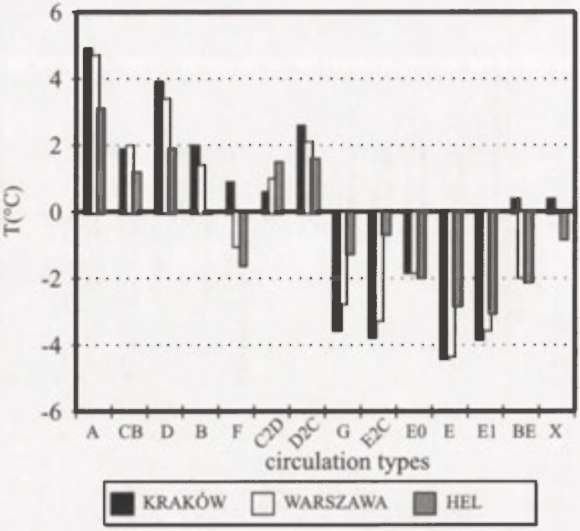

Figure 3. Deviations from the mean maximum air temperature (°C) under different circulation types – January.

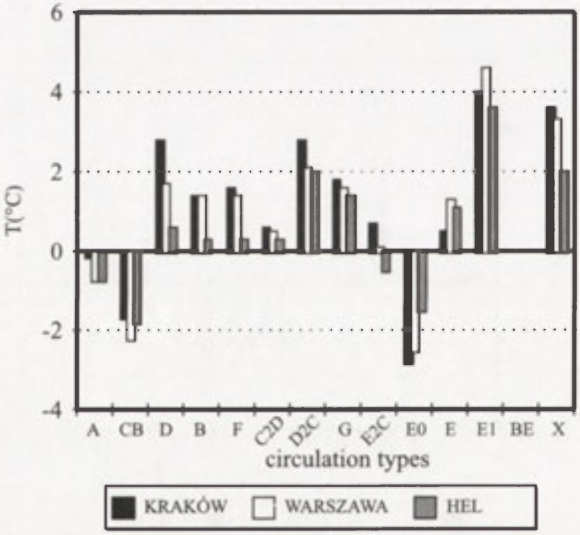

Figure 4. Deviations from the mean maximum air temperature (°C) under different circulation types – July.

only slightly lower. In July the influence of the particular types are quite different (Fig. 4). The highest positive deviations can be observed with the anticyclonic situation with a south-easterly or easterly airflow (E1). Negative deviations at all stations can be noticed with types E0 (north-easterly and easterly cyclonic) and CB (north-westerly cyclonic). It is worth noting that negative deviations happen with the westerly cyclonic situation (A), i.e. the one causing the greatest positive deviations during the winter.

FREQUENCY AND PROBABILITY OF EXTREME VALUES OF AIR TEMPERATURE

The dependent relationships mentioned above, received on the basis of mean extreme air temperatures will given circulation types, can also be observed in regard to the analysis of particular cases of such air temperature. For example, the highest probability of the occurrence of very cold days (t min < –15°C) can be invoked with the G, E2C and E types (Fig. 5). Similar dependencies, but with Grosswetterlagen circulation types have been obtained by Piotrowicz (1998). In Kraków it reaches about 25%, in Warszawa about 20%, at all 3 situations. A much lower probability, of just below 5%, can be observed in Hel, where the number of frosty days is altogether insignificant. It is worth noting that the occurrence of days with a minimum air temperature below –15°C is possible during all synoptic types in Kraków although such a probability can be rather low (below 5%) with some of them. This is also true of type A, which generally brings warm air advection in winter. There is also a smaller probablity of such days in Warszawa than in Kraków in most circulation situations (the only exception can be seen with type E0 and very seldom with BE). This particularly concerns types A and B when in Warszawa a day with a minimum air temperature below –15°C can not occur. Such differences result from the location of Kraków in the deep Vistula valley where thermal inversions and rapid decreases in minimum air temperature are quite frequent phenomena in the winter time. The highest probability of warm days (maximum air temperature above 25°C) in July can be observed during E1 situations (95% in Warszawa; Fig. 6). In the

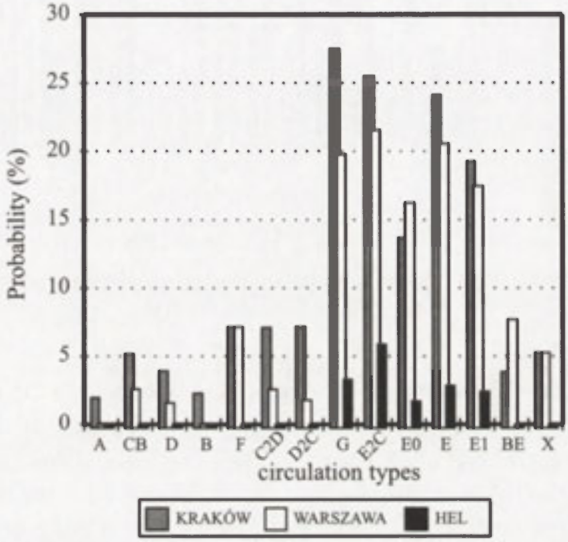

Figure 5. Probability of days with minimum air temperature < –15°C in January under different circulation types.

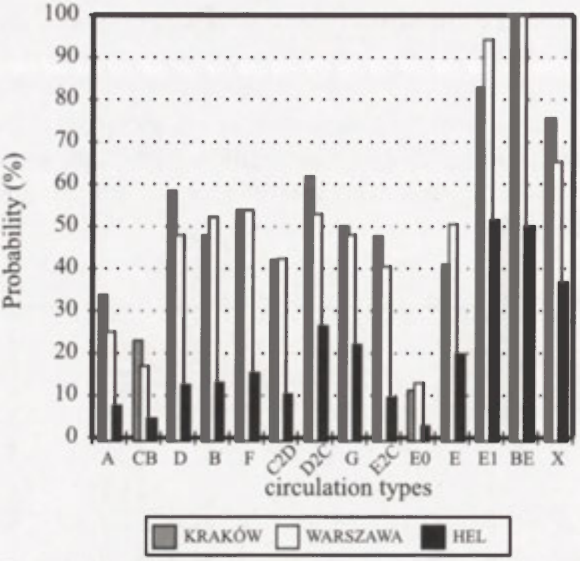

Figure 6. Probability of days with maximum air temperature >25°C in July under different circulation types.

presented figure the 100% probability can also be seen with the BE type in both Warszawa and Kraków. However, the very low frequency of this type in July (only 2 cases in the whole investigated period) does not allow any conclusion to be formulated. The lowest probability can be observed with the E0 type and reaches about 10% in Warszawa and Kraków (in Hel it only exceeds 1%). It is worth stressing that warm days can occur in the mentioned stations during all the particular circulation types. This means that atmospheric circulation is of more limited weather and climatic importance in summer than in the winter season. Because of the small number of hot days (with a maximum air temperature over 30°C), a statistical probability estimation and analysis was not available.

A certain amount of attention was also paid to the occurrence of absolute maximum and minimum temperature values. Because the synoptic source of these air temperatures is similar throughout the country (Niedźwiedź and Ustrnul 1994), the analysis was performed for Warszawa and Kraków. It must be added that extreme values very close to the presented ones can also be noted throughout southern and central Poland other than in the mountainous regions (Limanówka, Niedźwiedź, Ustrnul 1993). For example, the absolute maximum air temperatures in the analysed period reach 35°C while the absolute minimum values go down to –30°C. On account of the major importance of the causes of such extreme temperatures for forecasting purposes, an analysis of all cases with a minimum air temperature below –20°C or a maximum air temperature over 30°C has been performed. Days with maximum air temperature over 30°C occurred with all circulation types which confirms the opinion that the role of circulation is smaller in summer than in winter. With particular circulation types some differences in

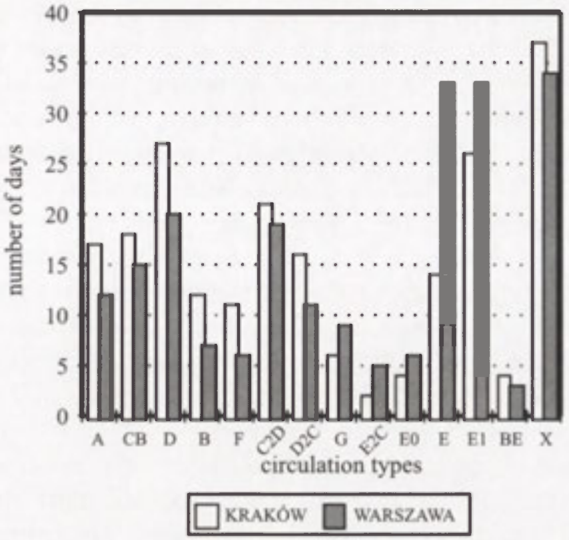

Figure 7. Number of days with maximum air temperature >30°C under different circulation types.

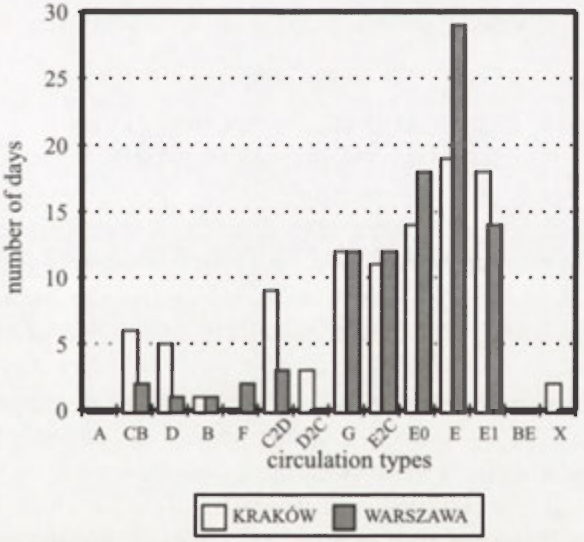

Figure 8. Number of days with minimum air temperature < –20°C under different circulation types.

the number of such days between Warszawa and Kraków could be noted (Fig. 7). This distinctly confirms the smaller macroscale role of circulation and the larger influence of local factors including mesoscale circulation. Thus, with types of westerly advection or the whole southerly sector the number of days of the kind considered is higher in Kraków than in Warszawa. This especially concerns situations D (south-westernly cyclonic), B (southernly cyclonic) and F (southeasternly cyclonic) when the higher air temperatures in Kraków can be explained by reference to the advection of warm tropical masses sometimes additionally warmed by foehn effects. The absolute air temperature maximum in Kraków happened during a BE situation (southern between cyclonic and anticyclonic) in August 1992, when 36.7°C was reached (a maximum of over 35°C occurred 4 times with D, X, E0 and BE types). At the same time, circulation types with an easterly advection are associated with a greater number of days with a maximum air temperature over 30°C in Warszawa. However, the greatest number of such days occur during type X (unclassified) situations in both places. It means that the applied Osuchowska-Klein classification does not define some significant circulation situations.

A much smaller differentiation to circulation types can be observed with regard to minimum air temperature below –20°C. 98 such days were noted in Warszawa and 105 in Kraków in the entire investigated period of 49 years. Most often they occurred with situations of the E type and other situations with an airflow from the easterly sector (Fig. 8). The absolute air temperature minimum in Kraków was noted during the E0 situation on 13 January 1987 (–29.9°C). It is worth noting that over 10 days with a minimum air temperature below –20°C occurred with a central anticyclonic situation (G) as compared not a single day with the westerly cyclonic type (A).

VARIABILITY IN THE NUMBER OF SPECIFIC DAYS AGAINST THE BACKGROUND OF CIRCULATION

The last phase, saw an introductory climatological analysis of the long-term series containing the number of days with specific extreme temperatures from Warszawa and Kraków. This was investigated against the background of some circulation indices. Such a method of simultaneous analysis of climatic data and circulation conditions allows natural climatic variability to be determined. Necessity of such studies has been noted by many climatologists (e.g. Yarnal 1993; Trenberth 1995), who recognise their usefulness not only for the prospective purposes but also for some modelling approaches.

Data concerning monthly and seasonal numbers of such days as well as indices originated from the same period 1951–1999. Atmospheric circulation was represented by different circulation indices (according to own approach, Ustrnul 1998 and on the basis of Osuchowska-Klein type frequencies). All the variables mentioned above were under correlated. This was possible because most series applied have a normal or quasi-normal distribution. The analysis revealed rather close dependencies between some specific days and circulation conditions. The strongest correlation was calculated for connections between the number of cold days (tmin < –10°C) and westerly and non-advection indices for winter (correlation coefficient = –0.71, 0.53, respectively), the number of very cold days (t min

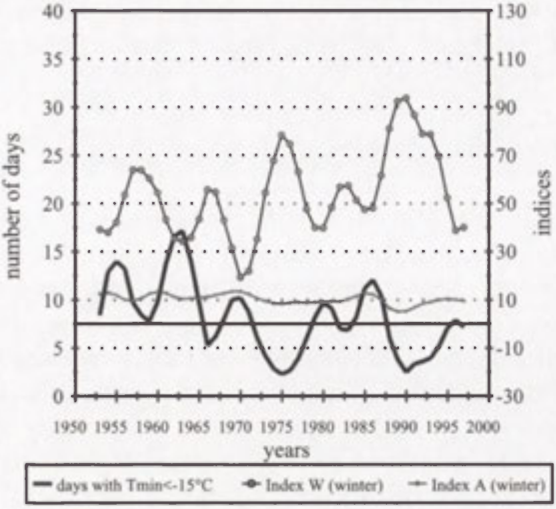

Figure 9. Number of days with minimum air temperature < –15°C in Krakow against the background of circulation (values smoothed by 5-element Gaussian filter; explanations in text).

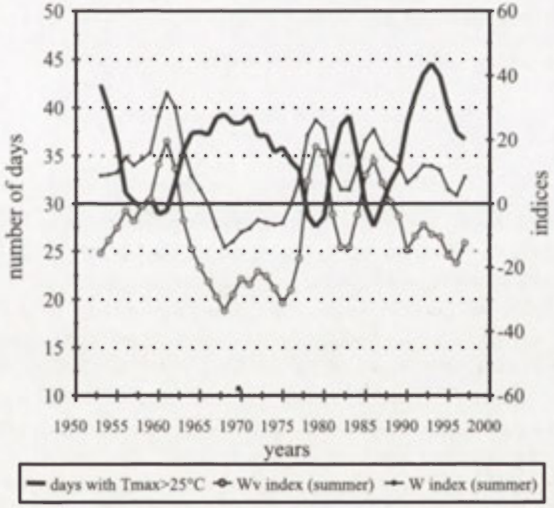

Figure 10. Number of days with the maximum air temperature > 25°C in Warszawa against the background of circulation (values smoothed by 5-element Gaussian filter; explanations in text).

< –15°C) and westerly and non-advection indices for winter (–0.74, 0.52, respectively; Fig. 9). A relatively good relationship was also detected for the number of warm days (t max > 25°C) and westerly indices for summer (r = –0.76 and r = –0.75; Fig. 10). The analysis revealed rather weaker dependencies between

some other variables (e.g. number of days with large daily amplitudes, frosty days (t max > 0°C and t min < 0°C)) and the circulation indices.

CONCLUSIONS

The analysis fully confirms the significant influence of atmospheric circulation upon the occurrence of extreme temperatures. The influence is much larger than other local factors (e.g. local relief and circulation), especially where maximum temperature values are concerned. Minimum extremes can be modified by radiation to a higher degree, while this is more clear expressed in winter than in summer. Taking into account the long observation period as well as the calendar for circulation types it is possible to determine the probability of the occurrence of specific extreme temperatures for each meteorological station and for the particular month and/or season. Such information is very useful from the practical point of view because it allows for an estimation of the size of the threat posed by extreme air temperatures. It can especially be used for forecasting purposes. The close relationship between circulation and extreme air temperatures can also be confirmed on the basis of the typical climatological approach. The dependencies between some number of days with specific extreme temperature thresholds and circulation indices are very close.

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20TH-CENTURY VARIABILITY TO DAILY MAXIMA AND MINIMA OF AIR TEMPERATURE IN THE SUDETIC MOUNTAINS

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ABSTRACT: The work presents the results of research on the variability to the 24-hour air-temperature maxima, minima and amplitudes noted in the period 1901–1998 on Śnieżka – the highest peak in the Sudetic Mountains. Analysis of a 98-year measurement series revealed the presence in the area of overall, statistically-significant upward trends for maximum temperature (of 0.06°C/10 years) and minimum temperature (0.12°C/10 years), as well as a downward trend for 24-hour amplitude (of –0.06°C/10 years). This points to ongoing warming and a weakening of the annual cycle to air-temperature variations in the summital zone of the Sudetic Mountains. Research on variability within thermal sequences made use of the Mann-Kendall test and revealed steady upward trends for extreme temperatures in the second half of the 20th century only, as well as a downward trend for amplitude that has been confined to the last 25 years.

KEY WORDS: variability of air temperature, climate change, Mann-Kendall test, Sudetic Mountains.

INTRODUCTION

Research into the variability of the climate in the Sudetic Mountains is an important regional element of present-day assessments concerning changes in the Polish climate. It is also justified in terms of the local needs of the population in the Lower Silesia voivodeship (region) as regards the protection of the environment, including the reinstatement of forest communities in areas threatened ecologically (Fabiszewski and Wojtuń 1994).

An earlier work by the author (Głowicki 1998) presented a 95-year series of mean monthly and annual values for air temperature on Śnieżka (φ = 50°44'N, λ = 15°44'E, H = 1603 m a.s.l.). This attested to ongoing 20th-century warming of the climate in the most-elevated hypsometric zone of the Sudetic Mountains. The linear regression coefficient for this 95-year series of mean annual air temperature on Śnieżka had a value of +0.7°C/100 years and is in line with the latest assessments of the rate of global warming (IPCC 1995). In the face of undiminished and considerable supplies of sulphur dioxide from nearbly coal-fired power stations (of the so-called "Black Triangle"), the assumed further upward trend to temperature may soon lead to a transformation of the system of altitudinal climatic and vegetational zones within this mountain massif. Such fears, justified by the results of technical monitoring of Sudetic spruce stands, are now being expressed by numerous ecologists and foresters (Fabiszewski and Wojtuń 1994; Zientarski 1993).

Scenarios of anticipated ecoclimatic transformations in the Carpathians assume a raising of the treeline of 200–700 m in the next 100 years (Obrębska-Starklowa et al. 1994; Kożuchowski 1996).

The aim of this study is to make a further assessment of the structure of the variability to the climate of the Sudetic Mountains in the 20th century, by documenting trends to the long-term course of daily maxima and minima, as well as the amplitude to daily temperature, on Śnieżka. A basis for the work was provided by a unified series of measurement data assembled at the local Meteorological Observatory in line with a uniform observation standard over the period 1.01.1901 to 31.12.1998. The homogeneity to the genesis of the data is guaranteed by constant locations for maximum-minimum thermometers within the measuring box on a measurement terrace elevated some 15 m above the summit of Śnieżka (Glowicki 1995). The Observatory's location on the highest peak in the Sudetic Mountains, and hence beyond the direct range of human economic impacts, allows for the obtainment of empirical data necessary in identifying "natural" symptoms of climatic variability associated first and foremost with the impact of astronomical and geological factors, as well as the circulation of the atmosphere (Lorenc 1994).

METHODS

The analysis encompassed a 98-year time series of mean monthly and annual values for daily minima, maxima and amplitudes of air temperature on Śnieżka in the years 1901–1998.

With a view to identifying long-term trends to changes among the selected thermal characteristics, coefficients for the linear trend were calculated for the entire analysed period. The statistical significance of trends was then studied with the aid of a *t*-Student test. The assessment of temperature variability within the analysed measurement series was in turn achieved using the non-parametric Mann-Kendall rank test, in the version modified by Snyers (1990) and popularised in the Polish literature by Mitosek (1994). The $U(t)$ statistic from the aforementioned test is determined progressively (moving forwards or backwards through time), in accordance with the formula:

$$U(t_i) = [t_i - E(t_i)]/\sqrt{\mathrm{var}(t_i)},$$

where: ti is the sum of ranks of the analysed series (or parts there of) and $E(t_i)$ and var (t_i) are the expected values for the mean and variance (assuming stationarity of the process).

In turn, absolute values for the $U(t)$ statistic were calculated as ordered through the 98-year series. These pointed to the chance of a trend occurring or being absent (assuming a significance level $\alpha = 0.05$), while the positive or negative sign suggested the direction (upward or downward). On the basis of the test analysis of time series it was possible to identify the durations and directions of designated trends to the variables studied – as the result of the grouping of low or high values in successive events (Mitosek 1994). The final element in the form of the $U(t)$ statistic for the whole 98-year time series also allowed for the uncovering of any general long-term trend (or reporting of its absence) to the full observational series of daily air temperature maxima, minima and amplitudes on Śnieżka in the years 1901–1998 (Tab. 1).

RESULTS AND DISCUSSION

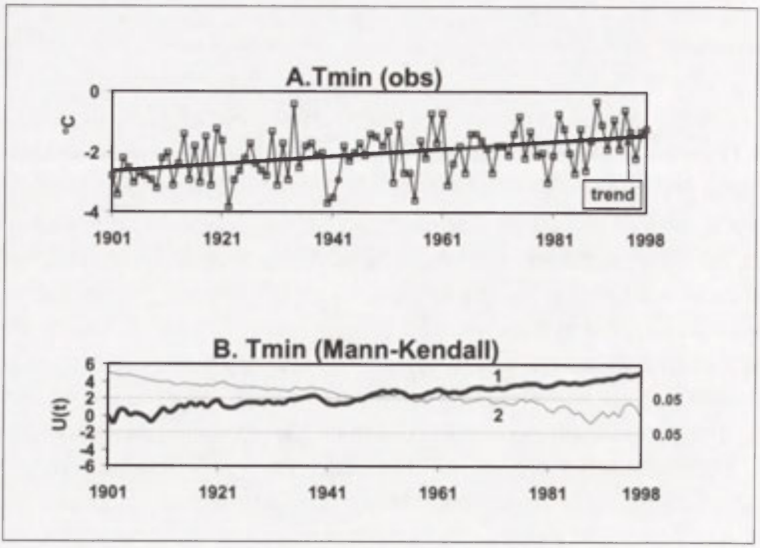
The basic feature to the variability of daily air temperature maxima and minima on Śnieżka through the century has been the overall upward trend, within which the most marked rate of change has been noted for August and the steadiest tendency for the winter months.

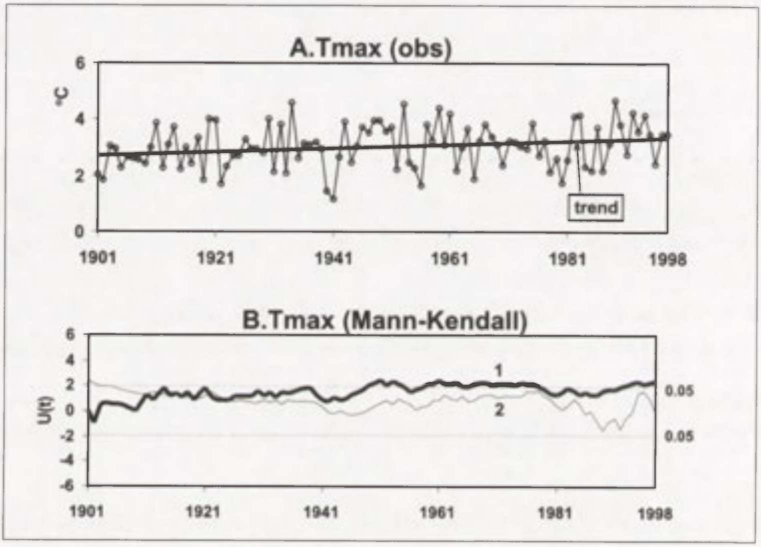
Data in Table 1 indicate that only half of the 98-year series of monthly mean values for daily minimum air temperature are characterised by a statistically-sig-

Table 1. Statistics assessing the variability and trends to mean monthly and yearly values for daily minima (T_{min}), maxima (T_{max}) and amplitudes (T_{amp}) of air temperature on Śnieżka in the years 1901–1998.

Period (month or year)	Linear trend (°C/10 years)			Result of Mann-Kendall test (progressive statistic)		
	T_{min}	T_{max}	T_{amp}	T_{min}	T_{max}	T_{amp}
January	0,12	0,07	–0,05	1,64	1,18	–1,94
February	0,17	0,11	–0,06	2,05*	1,33	–1,33
March	0,07	0,02	–0,05	0,98	0,43	–1,53
April	0,14*	0,09	–0,05	2,38*	1,27	–1,48
May	0,08	0,04	–0,04	1,74	0,58	–2.14*
June	0,14*	0,05	–0,09*	2,83*	1,22	–3,05*
July	0,12*	0,03	–0,08*	2,32*	0,63	–2,88*
August	0,22*	0,15*	–0,07*	4,94*	3,03*	–2,42*
September	0,11	0,04	–0,07*	1,97*	0,78	–2,14*
October	0,15*	0,12	–0,03	2,19*	1,95	–0,73
November	0,13*	0,04	–0,09*	2,16*	0,83	–3,14*
December	0,06	0,00	–0,06*	1,35	0,33	–2,20*
YEAR	0,12*	0,06*	–0,06*	5,02*	2,34*	–4,98*

* denotes trend significant at $\alpha = 0.05$.


A.Tmin (obs)
°C
0
-2
-4
trend
1901
1921
1941
1961
1981
1998
B. Tmin (Mann-Kendall)
U(t)
6
4
2
0
-2
-4
-6
1
2
0.05
0.05
1901
1921
1941
1961
1981
1998


A.Tmax (obs)
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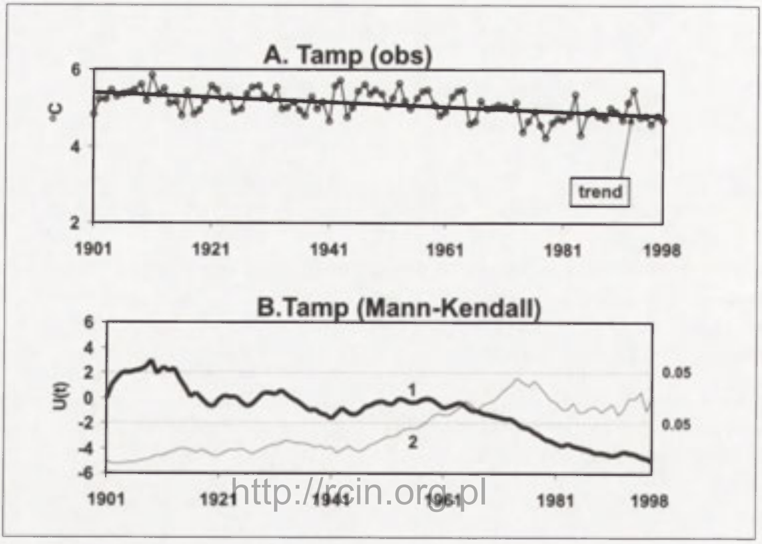
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nificant linear trend. Marked upward trends occurred in the time series for April, June, July, August, October and November. In the case of the relevant monthly series for daily maxima, the adopted significance criterion ($\alpha = 0.05$) was only met by the series for the month of August. Mean annual values for daily air temperature minima and maxima are characterised by significant upward trends, with respective values of +0.12 and +0.06°C/10 years. The finding of a rate of increase to daily minima that is twice as great as that for maxima is in line with many quantitative assessments now to be documented in both Europe (Brázdil et al. 1995) and other continents (Karl et al. 1993).

Thus, the courses for daily amplitudes of air temperature on Śnieżka across the period 1901–1998 show a dominant downward trend for all months. The coefficient for the linear trend over the 98-year series of mean annual values is –0.06°C/10 years.

The results of the search for trends within the 98-year time series using the course of the $U(t)$ statistic from the Mann-Kendall test did not confirm any occasions of prolonged thermal trends on Śnieżka in the first half of the 20th century. Major changes in the long-term courses of the analysed indices of air temperature only began at the beginning of the second half-century. It is possible to adopt, as the beginning of periods with a sustained trend towards change in the analysed thermal characteristics, the points presented in Figure 1 of the intersection of curves to the course of the relevant progressive and regressive $U(t)$ test statistics.

The Mann-Kendall test allowed the presence of a significant upward trend to minimum air temperature on Śnieżka to be identified for the period 1936–1939, and again for the next 51 years (1948–1998), i.e. altogether for some 56% of the whole series. Less-sustained significant upward trends for daily maxima emerged in the cases of three short periods: 1949–1954, 1959–1977 and 1992–1998, i.e. over a total of 32 years. Mean annual values for amplitudes to daily air temperature showed a weak upward trend at the beginning of the analysed series (years 1904–1913), while the last 25 years of the period (1974–1998) witnessed a marked downward trend.

CLOSING REMARKS

Signs of global warming noted in the summital zone of the Sudetic Mountains are most clearly marked when it comes to the significant upward trend for daily air-temperature minima. The mean annual minimum air temperature on Śnieżka increased by 1.2°C in the years 1901–1998, while the maximum temperature

Figure 1. Time series of mean annual value for daily minima (T_{min}), maxima (T_{max}) and amplitudes (T_{amp}) of air temperature on Śniezka in the years 1901–1998.

A – observational data and linear trend, B – statistic for Mann-Kendall rank correlation, 1 – progressive statistic, 2 – regressive statistic.

increased by 0.6°C. The consequence of such changes was a 0.6°C (11%) decline in the amplitudes of daily air temperature over the 98 years. However, sustained thermal trends only made themselves apparent in the second half of the 20th century.

At the present stage of the research it is difficult to come up with an unambiguous interpretation of the causes of the temperature changes observed on Śnieżka, where both maxima and minima are correlated inversely with the total cloud cover. The role of aerosols from the many nearby coal-fired power plants (of the so-called "Black Triangle") may not be without significance.

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VARIABILITY IN THE CLOUD COVER OF THE KARKONOSZE MOUNTAINS OVER THE LAST CENTURY

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ABSTRACT: The study details an analysis of cloudiness conditions over Śnieżka Mountain in the years 1885–1995. The basis for this constituted timed observations (at 7,13 and 21 hrs) of cloud cover and mean daily cloud amount in particular months, seasons and the whole year, as well as the number of clear, overcost and foggy days. The variability to cloud cover was found to feature an upward trend of 0.4/100 years which is most clearly seen in the autumn quarter. There is a tendency for the number of clear days to decrease (by 22 days/100 years), and for the number of days with fog to increase, most especially in winter (10.4 days/100 years). A link between cloud cover and the frequency of occurrence of the western-circulation macrotype has been noticeable in the last 40 years.

KEY WORDS: cloudiness, secular series, trend analysis, climate change, Sudetic Mountains.

PRELIMINARY REMARKS

The systematic observation of cloudiness in the Karkonosze Mountains was begun on Śnieżka Mountain in 1885, having been carried on periodically from as early as 1824. This continuity of observation ensures that this is one of the few long observational series from the summital parts of Central Europe's mountains.

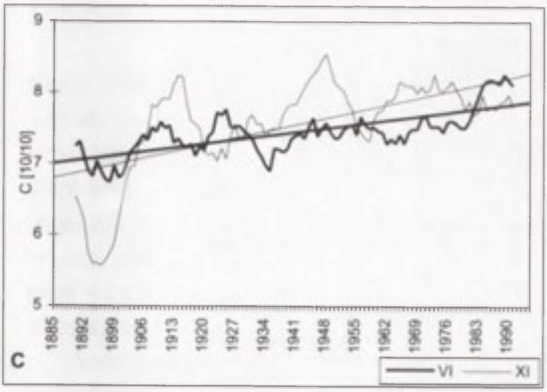
The role of cloud cover in the theory of climatic warming is not yet fully defined. Physical research into the natural properties and anthropogenic changes to the climatic system needs to take account of very detailed observational material and become acquainted with the peculiarities of its long-term course for different parts of the day. However, the empirical work being done to better understand long-term global-warming-related variability to cloudiness in different parts of the globe (Henderson-Sellers 1986, 1989; McGuffie et al. 1990) has not yet come to include a study of cloudiness through the daily cycle.

Analysis of the long-term course of cloudiness on Śnieżka made use of uniform series of timed observations (3 times a day at 07.00, 13.00 and 21.00 h), as well as mean daily cloudiness for different months, quarters and years in the period 1885–1995 – all obtained from the collections of the Institute of Meteorology and Water Management. This study has also taken under consideration the number of clear, cloudy and overcast days, as well as the low-level of cloud cover in the years 1967–1997. The uniformity of the observational series was not influenced by the change in the time of observation of cloudiness from 14.00 to 13.00, or by the shift from using a 10-point to an 8-point scale in determining the level of cloud cover (1980).

VARIABILITY IN CLOUDINESS

The mean annual cloud amount on Śnieżka amounted to 7.4. Mean five-year magnitudes were in the range 6.7 (1891–1895) to 7.7 (1911–1915; 1941–1945). The lowest mean value for annual cloud cover of the sky was the 6.2 noted in 1921, and the highest the 8.2 recorded for 1912 and 1941 (Tab. 1). The hours of the afternoon are the cloudiest within the daily cycle (7.7 at 13.00), while the evening (21.00 h) observations reveal the least cloudiness (7.0). Year-round, the highest level of cloud cover in the summital parts of the Karkonosze is that noted in March and November (7.5), and the lowest the figure of 7.1 obtained for August. A characteristic feature of cloudiness is the way it varies greatly from year to year. In different years, the mean monthly cloudiness has ranged from 1.7 (in April 1906) to 9.6 (in October 1974). The greatest variability to cloudiness is that noted in the evenings of the autumn quarter, most especially in the month of September. The minimal variability is that occurring in March, while evening of cloud amount also differs little in July and June. In turn, the lowest degree of variability to cloud cover through the day is that noted in the afternoon between May and August. Such a high degree of variability to cloud cover hinders the obtaining of regularities and trends for it. In the long period under analysis, there are two periods that stand out where the course of cloudiness was concerned. These are 1885 to the mid 1950s, during which term cloud cover showed a high degree of variability, as well as an overall upward trend; and the last decade of the 20th century in which the observational series is characterised by the low-level of cloud cover (Fig. 1). The latter observation, as well as the greatest rise in cloudiness being maintained to the middle of our century's second decade, has also been observed at other stations in Europe. It finds confirmation in the course obtained for cloudiness in the Alps, for example, at the Saentis, Grand-St-Bernard and Hohenpeinssenberg stations. From 1912 onwards, there was a clear trend towards a decline in cloudiness that was observed in the light of both mean annual figures and seasonal (other than autumn-quarter) ones. A return to an increase in cloudiness was to be observed in the decade 1931–1940, albeit with lesser amplitude to changes being a feature characteristic of evening observa-

Figure 1. Cloudiness on Śnieżka in the years 1885–1995.
Curves smoothed by 10-year moving average and linear trends.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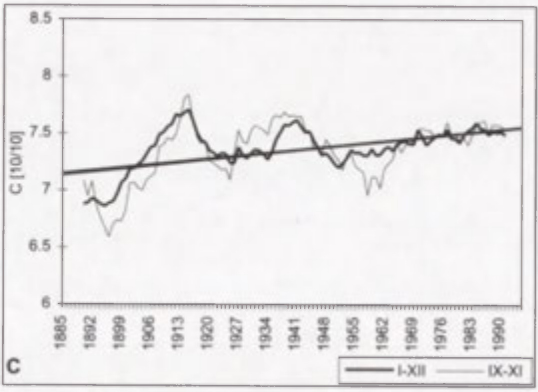
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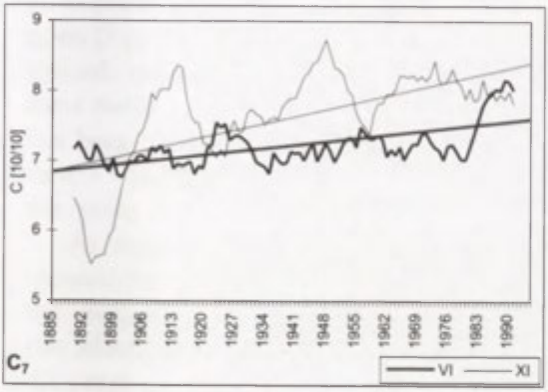
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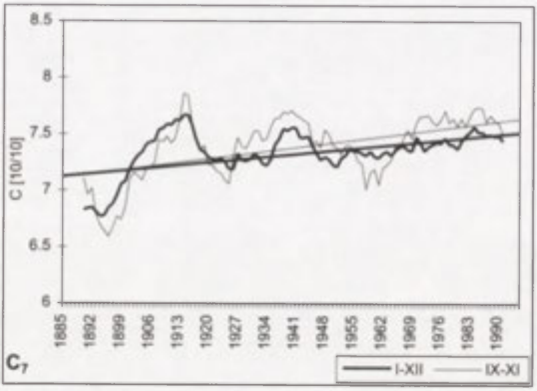
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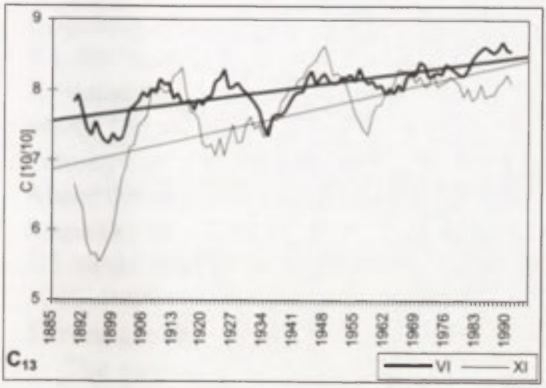
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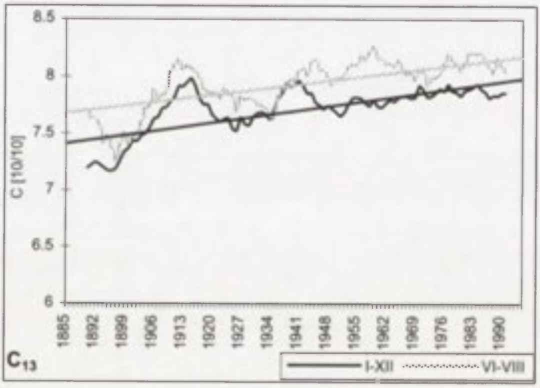
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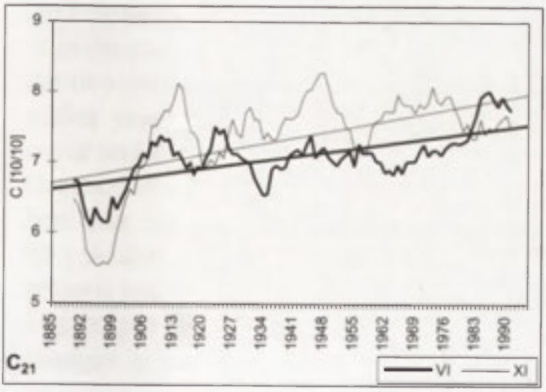
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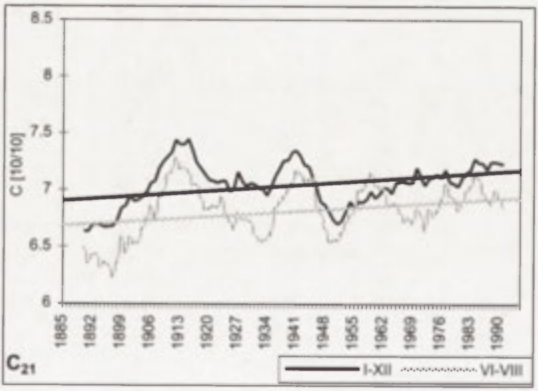
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Table 1. Mean monthly, seasonal and annual cloud amounts and number of clear, overcast and foggy days on Śnieżka in the years 1885–1995.

	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	XII-II	III-V	VI-VIII	IX-XI	XI-IV	V-X	I-XII
Ci	7.2	7.4	7.5	7.4	7.3	7.4	7.3	7.1	7.2	7.3	7.5	7.4	7.3	7.4	7.3	7.3	7.4	7.3	7.4
C7	7.3	7.5	7.6	7.4	7.0	7.2	7.2	7.0	7.2	7.3	7.6	7.4	7.4	7.4	7.2	7.4	7.5	7.2	7.3
C13	7.4	7.5	7.7	7.9	7.9	8.0	8.0	7.8	7.6	7.4	7.6	7.5	7.5	7.8	7.9	7.6	7.6	7.8	7.7
C21	7.0	7.3	7.4	7.0	6.8	7.1	6.8	6.5	6.7	7.2	7.3	7.2	7.1	7.1	6.8	7.1	7.2	6.9	7.0
no. of days:																			
Ci < 20%	4.0	3.1	2.7	2.1	1.5	1.3	1.3	1.9	2.6	3.2	3.0	3.5	10.6	6.3	4.6	8.8	18.3	12.0	30.3
Ci > 80%	17.4	16.3	17.7	16.0	14.9	15.1	14.8	14.0	14.7	16.7	17.7	17.8	51.3	48.6	43.9	49.2	102.5	90.2	193.1
foggy	25.2	23.2	26.1	23.7	23.4	23.1	22.9	22.9	24.1	26.0	25.1	25.5	73.6	73.1	68.8	75.2	148.2	142.3	290.9

C7, C13, C21 – observation of cloudiness made at 7,00, 13,00 and 21,00 h. Ci mean daily cloudiness tions. The second half of the 20th century was in turn characterised by lesser variability to cloud cover from year to year. With the exception of in the morning observation time in the summer quarter, it was positive deviations from the long-term mean that prevailed. This was particularly clearly denoted in the evenings, during which greater-than-average cloudiness was sustained in the summer, winter and spring quarters from the mid 1930s onwards. This increased cloudiness on the annual course as a whole was seen in the evenings, especially in the autumn and spring quarters.

Across the 110-year study period, mean annual cloudiness on Śnieżka showed an upward trend that was significant at $p = 0.05$ and most marked in the afternoon (Fig. 1). In the light of the figures obtained for daily mean values, the trend towards increased cloudiness was found to be clear at all times of the year, albeit most distinct in the autumn quarter. A similar regularity to changes in cloudiness has been observed in the afternoons also, especially in the summer months. In turn, a non-statistically-significant trend towards increased cloudiness was noted for spring and autumn evenings and summer mornings.

As regards the different months, it was November, followed by June, that showed the greatest trend towards increased cloud cover. This is seen clearly in the comparison of frequencies of mean monthly figures for cloud cover in the two identified periods of the 110-year series. It is also worth noting that the last 40 years of the 20th century have been characterised by an increase in the frequency of cloud amounts in the higher classes, as for example in June (classes 8.1–9.0 noted almost twice as frequently as in the years 1885–1955, Fig. 2). A statistically significant increase in cloudiness over 10 months (excluding March and December) has been noted in the afternoons, and over 5 months in the evenings. A downward trend for cloudiness is confined to October, especially where the evenings and values for daily averages are concerned. In October, the frequency of mean monthly cloud covers in the range 8.1–9.0 was found to be 3.5 times lower when the period 1956–1995 was compared with the period 1885–1955. The frequency of occurrence of class 5.1–6.0 cloudiness was in turn 5 times greater.

The upward trend to cloudiness is very much correlated with an increase in the frequency of western circulations. However, close linkage can only be spoken of in the case of the autumn quarter. In other seasons of the year, the link between the two variables has only appeared in the last 40 years. On the other hand, in earlier years there is a lack of any clear relationship between increased cloud cover and the frequency of the western circulation macrotype according to the Osuchowska-Klein classification. What was probably an important influence here was the fact that the calculated correlation coefficients (according to the 95-year data series) for the value of the mean degree of cloud cover in different seasons and the year as a whole against the frequency of the western circulation macrotypes for these periods was not statistically significant. Nevertheless, the changes in atmospheric circulation, at least in recent years, indicate that this is

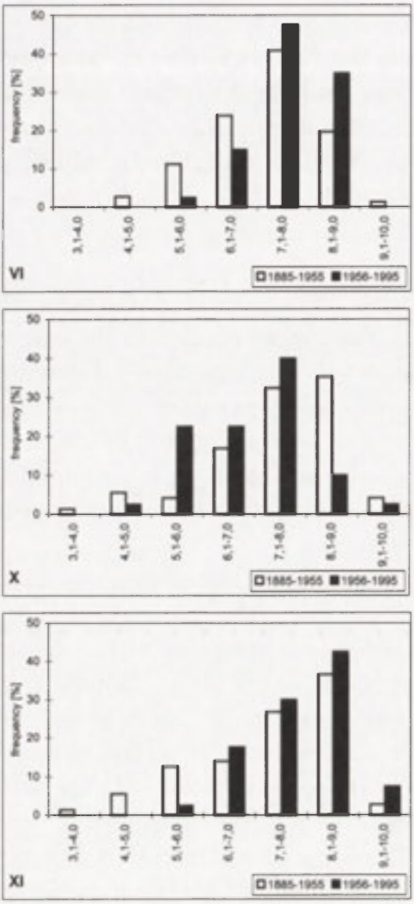

Figure 2. Frequency of mean monthly cloud amounts on Śnieżka in selected months of the periods 1885–1955 and 1956–1995.

a fundamental element in the interpretation of climate change. Many authors, including Kożuchowski (1994, 1995) have stated that the greatest positive departures of the zonal circulation over Europe in the 1980s were those occurring in the autumn and winter seasons. The cool half-year (October-March) has also been distinguished as a period with a high frequency of deep cyclones. Similar results were obtained by Niedźwiedź et al. (1994), who carried out research on the frequency of zonal types of circulation of the atmosphere over the Carpathians.

VARIABILITY OF CLEAR OVERCAST AND FOGGY DAYS

The mean annual number of fine days on Śnieżka is 30.3, while the range is between 10 (in 1955) and 70 (1892, 1893). The greatest variability is that noted for spring and summer months (April-August). Fine days have been the subject of a downward trend (of 22 days per 100 years), that is statistically significant at

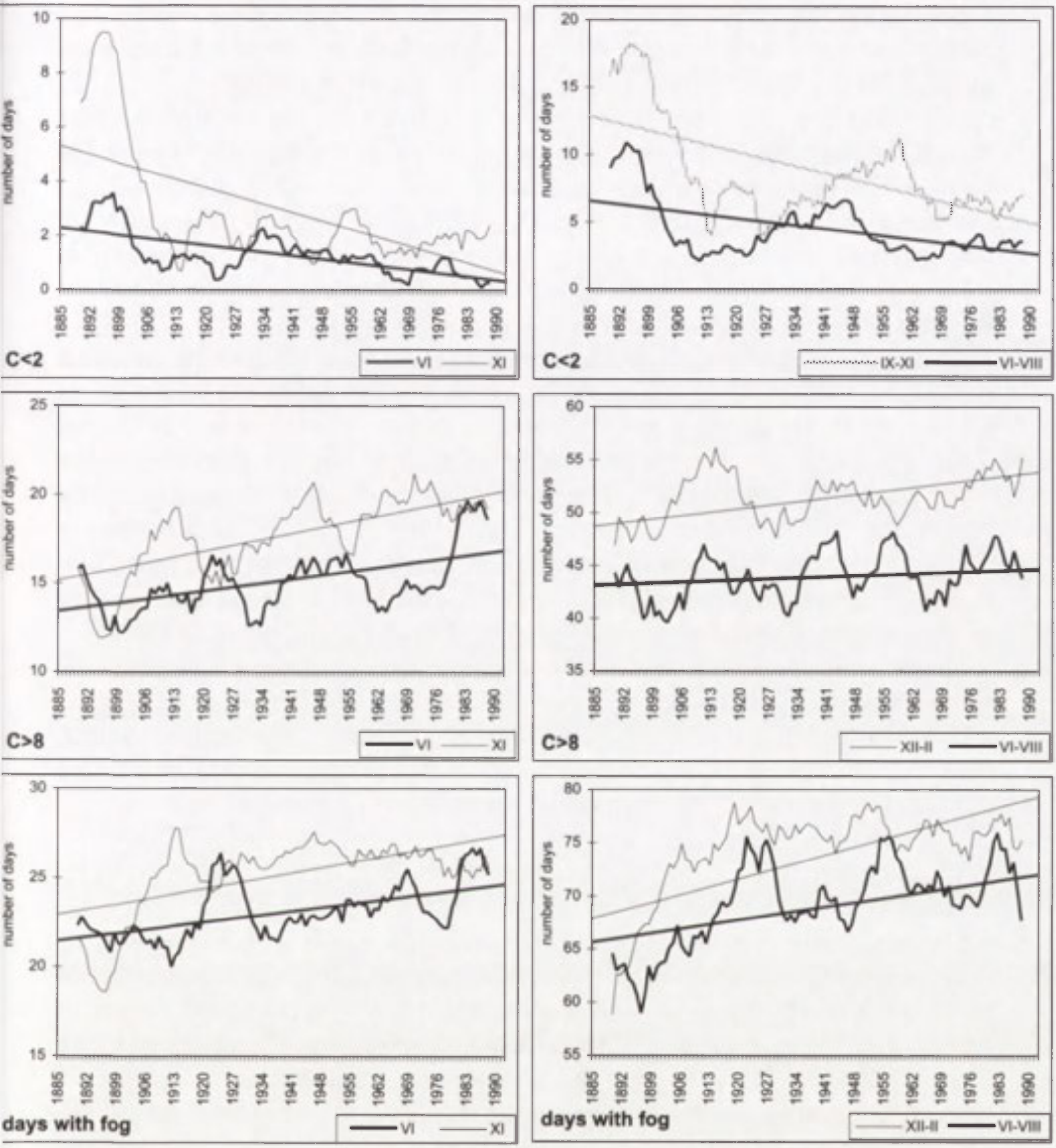

Figure 3. Number of clear, overcast and foggy days on Śnieżka in the years 1885–1995. Curves smoothed by 10-year moving average and linear trends.

the p = 0.05 level (except in July and October). This has been most marked for the autumn months, especially November. The decisive factor in this case was the greatest decline noted in the late 19th and early 20th centuries (Fig. 3). As regards the course to the number of fine days in the spring and summer quarters, two periods are identifiable. The first – of a slight increase – stretched from the beginning of the 20th century to the end of the 1940s, while the second, of a decline that was initially marked, began in the 1960s with considerably less variability from year to year. A different course, with much more limited variability, characterises the course of clear days in the winter quarter.

Cloudiness is observed in the course of 193.1 days. In the period under discussion, the value from year to year varied between 138 days in 1921 and 254 in 1941. The greatest variability was characteristic of the spring months (May) and those of autumn (September, October). There was a statistically-significant upward trend to the number of cloudy days (of 4.7 days/100 years), but only in the winter quarter. An upward trend is to be noted in spring, from the mid 1950s onwards, and in autumn, from the beginning of the 1960s.

Fog is the meteorological phenomenon observed most often in the summital plateau zone of the Karkonosze Mountains. It occurs on 290.9 days a year on average, while the extreme range is between 246 days (in 1895 and 1993) and 336 (1941 and 1987). The greatest variability to its occurrence characterises the warm part of the year (April to September). Days with fog show a significantly significant upward trend in all quarters and in the year. This is most marked in winter (+10.4 days/100 years), especially in January. There is an upward tendency not achieving statistical significance in April, May and September, as well as a similar non-significant decline in the number of foggy days in October.

In the period under analysis there was a trend towards extreme changes in the weather situation on Śnieżka in November and June and in the winter quarter. This was manifested in all the characteristics considered, i.e. the number of clear, overcast and foggy days. The decline in the number of clear days was associated with an upward trend for the number of overcast and foggy days.

CLOSING REMARKS

Analysis of a 110-year series of observations of cloudiness and the number of clear, overcast and foggy days on Śnieżka Mountain revealed a high degree of variability from year to year. Mean annual cloudiness was characterised by an upward trend (0.4/100 years), but this was most notable in the autumn quarter. In relation to the basic observation times, the most distinct upward trend for cloudiness was that noted in the case of afternoon readings, and the least clear the trend for evening data. Clear days were subject to a downward trend. These changes were to be observed in all seasons and for the year as a whole (a downward trend of 22 days/100 years). However, a statistically-significant increase in the number of cloudy days was only to be noted for the winter quarter. The number of days with fog in turn showed a marked increase, especially in winter (10.4 days/100 years). When it came to the yearly course, the most distinct upward trends to cloudiness were those noted for November and June.

Upward trends for cloudiness in the plateau zone of the Sudetic Mountains correspond to a decline in the annual sunshine totals of 22 hours/100 years

– something that is particularly visible in the summer quarter, and above all in June – in connection with the greatest increase in cloudiness in the afternoon (Dubicka 1998). The observed trends to changes in cloudiness on Śnieżka are in line with research on global climatic warming in different regions of the world. In seeking to explain the increased cloud cover (especially in the parts of the day closer to night (7.00 and 21.00) in the cloud season), reference might be made to the upward trend for air temperature noted by Glowicki (1998) for Śnieżka, over the period 1901–1995. Karl et al. (1992) in turn ascribed a major role in explaining the more rapid rise in temperature minima than maxima to the increasing cloudiness and concentrations of anthropogenic aerosols in the lower troposphere. Jefimova et al. (1994) were in turn able to document a close link between the long-term course of air-temperature changes and cloudiness (especially in the cool season of the year).

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VARIABILITY TO THE FREQUENCY OF OCCURRENCE OF MASSES OF MARITIME AIR OVER NORTHERN AND CENTRAL POLAND IN THE 18TH TO 20TH CENTURIES

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ABSTRACT: The work seeks to reconstruct the frequency of occurrence of masses of maritime air over the area of central Poland in the period between the 18th and 20th centuries. The input material was linked up with mean monthly air temperatures in Berlin (1702–1778) and Warsaw (1779–1998). Changes in the frequency of occurrence of the aforementioned air masses in the course of the year have been treated as a rough measure of variability to the atmospheric circulation over the area in question (advections from the west). It proved possible to identify 7 periods characterised by changes towards increases (H) or decreases (L), or else by oscillations around the mean (M) frequency of occurrence of masses of maritime air over Poland: I. (... 1702–1725 (?); L), II. (1726(?) –1761; H), III. (1762–1796; M), IV. (1797–1899; L), V. (1900–1928; H), VI. (1929–1950; L) and VII. (1951–1998..., H).

KEY WORDS: climate change, 3 last centuries, atmospheric circulation, advections from the west, masses of maritime air, Poland.

The causes of climatic variability in the last several hundred years are being sought in the variability of large-scale atmospheric circulation. One of the measures describing this variability may be the changes in the frequency of occurrence of atmospheric masses. In the case of northern and central Poland, the frequency of occurrence of masses of maritime air (hereinafter Pm) may be treated as an indicator of changes in the frequency of advection from a sector between the SW and the NW, i.e. in general terms the west. The aim of the study has been to present the results of research on the frequency of occurrence of Pm masses over northern and central Poland in the last 300 years or so. Acknowledging the unknown quality of observational material from the 18th and early 19th centuries, the authors have tended to treat the results obtained with a certain degree of caution.

Early information on atmospheric pressure in Europe is hard to come by and the degree of certainty to be attached to it must be limited. There is rather more information about thermal changes, however, and the reliability would also seem to be greater. Furthermore, this information at least is capable of being verified by other methods. Thus information on temperature, characterising the overall heat balance (including the advection component) is therefore capable of providing certain component information on circulation conditions, as many researchers have already noted.

Even if temperature measurement is burdened by systematic errors, and even if a series is non-homogeneous, the annual amplitude of temperature should be less prone to error than the measurements themselves. Thus annual amplitude to temperature (A) allows for the calculation of a non-dimensional indicator of oceanity (Oc) in line with the formula:

$$\mathrm{Oc} = (0.732 \cdot j + 1.767) / A,$$

where: φ is latitude (degrees and tenths of degrees). The close link existing between the index of oceanity (with values in the interval 4 to 1) and the frequency of occurrence of masses of continental air (MK, %) expressed as a percentage of the year may be expressed by reference to the formula:

$$\mathrm{MK}\ (\%) = 166.66 - 75 \cdot \mathrm{Oc} + 8.33 \cdot \mathrm{Oc}^2,$$

which also allows for a definition of the frequency of occurrence of a maritime air mass in the course of the year, with a mean error to the estimate of ± 3.4%. Full justification of the method is to be found in Marsz (1995), and the above calculation procedure was adopted for further use in the work.

In order to analyse the frequency of occurrence of Pm masses, use was made of series for mean monthly air temperatures at the stations in Berlin (1702–1709, 1731–1751, 1756–1998), Warsaw (1779–1998), Copenhagen (1768–1998), Stockholm (1756–1998) and Saint Petersburg (1752–1998). In addition, comparisons were made with the shorter series available for Koszalin, Helsinki, Haparanda and Oslo, as well as the very long Central England series (Manley; 1659–1998).

Consideration of these series made it possible to calculate annual amplitudes of temperature for the November-October period (the hydrological year), as well as indices of oceanity and the frequency of occurrence of Pm masses. The values obtained were then subjected to further analysis (for clusters, distributions, correlations, etc.), and it was shown that the index of oceanity and the frequency of occurrence of Pm masses were correlated in given parts of the time series, and point to simultaneous characteristic variability in space (horizontal gradients). This indicates that the variability to circulation (towards greater oceanity or continentality) gave similar effects to those observed now (from year to year) over Central Europe and the Baltic basin. A particularly strong correlation is that between the parts of the series common to Berlin and Warsaw (r = 0.8716,

$p < 0.000\ 000$). This strong correlation between Warsaw and Berlin provided a reasonable basis for the generation of frequencies of occurrence of Pm masses in Warsaw on the basis of earlier data from Berlin (1702–1709, 1731–1751, 1756–1778). In this way was a combined series of data calculated for Warsaw from Berlin or from Warsaw itself was created for a period lasting between 1702 and 1998 (with the aforementioned short breaks), i.e. for nearly the whole of the 18th, 19th and 20th centuries. Some of the generated values (for 1702–1778) were however characterised by an increased error to the estimate of up to ±5.2%.

To eliminate short-period variability, this sequence was subjected to filters (moving average, smoothing by polynomial filters). The emergence of strong quasi-8-year periodicity and a relatively strong component periodicity of c. 11 years duration, led to the course to variability in the frequency of occurrence of Pm masses being presented as smoothed by a 13-point consecutive average (Fig. 1).

The discernment of periods of variability was achieved on the basis of deviation from courses from the long-term mean (35.95%), with deviation periods shorter than the length of the filter being ignored. This allowed for the identification of the following 7 periods within the course of the variability.

I. Years? – c. 1725(?), characterised by minimal frequency of occurrence of Pm, with the lowest value of all in the studied period (at c. 20%), which occurred around 1716 (?) – a year characterised by very low winter temperatures and low mean temperatures for the summer months. The year denoting the limit of the period is uncertain because of the discontinuity of the series, and was only designated by way of interpolation;

II. Years 1726(?) –1761, in which the frequency of occurrence of maritime air masses attained its absolute maximum throughout the observation period (c. 46% in the years 1732–1738), and in which – equally importantly – there was a high proportion of Pm masses present in the summer period (i. e. low mean temperatures for the summer months);

III. Years 1762–1796, a period in which the frequency of occurrence of Pm masses oscillated around the mean value (variation within the range 33–38%);

IV. Years 1797–1899; the longest period, and one characterised by a frequency of occurrence of maritime air masses reduced below the average – a dramatic decline for the years 1794–1811 (when the frequency reached its minimum of c. 27%) was followed by a series of at least 5 brief fluctuations of similar amplitude albeit with higher minima each time;

V. Years 1900–1928; a period of significant increase in the frequency of occurrence of maritime air masses plateau at 41–42% in the years 1904–1923, and followed from 1924 onwards by a deep and steady decrease in the frequency of occurrence;

VI. Years 1929–1950, with a decline in the frequency of occurrence of maritime air masses below the average and a minimum (less than 30%) in the years 1935–1941;

VII. Years 1951–1998(?); a period characterised by values above the average,

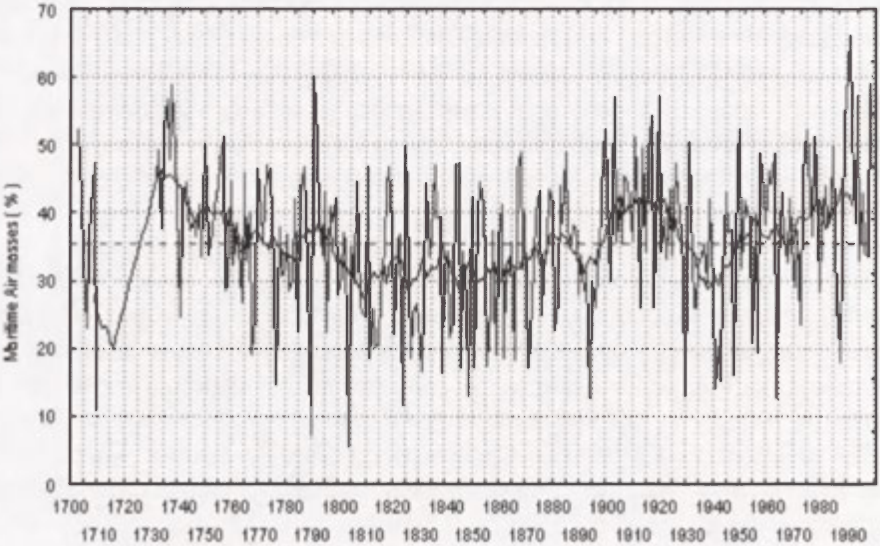

Figure 1. Frequency of occurrence of masses of maritime air in Warsaw (MPm %) expressed as a percentage of time during the year (combined sequence smoothed by 13-point moving average. Note: values for the period 1710–1730 are lacking and so have been interpolated).

with a "sawtooth" shape to the increase in the frequency of occurrence of maritime air masses (the two longer episodes of decline being in the 1960s and the period 1983–87) and no crossing of the mean value characteristic of period V.

The values given for the frequency of occurrence of Pm masses are characteristic for Warsaw and may also be taken as approximately characteristic for Central Poland. To the west and north-west, these values increase linearly as a function of distance from Warsaw, by up to c. 8%. The increase in the northern direction (towards the Gulf of Gdańsk) is of c. 6–7%.

No trend is to be noted across the analysed period of c. 300 years. The frequency of occurrence of masses of maritime air (MM) as a function of time is given by the regression equation:

$$MM(\%) = 34.720(\pm 1.502) + 0.00761(\pm 0.00829) \times no;$$

where no. is the successive year (with 1700 = 0).

The equation has a coefficient of determination equal to 0.00 (R = 0.06). The standard error to the estimation of the regression coefficient is greater than the value of the coefficient itself, thereby denoting that even the sign preceding the vector is not certain. In the face of this, it may be considered that no more significant long-term trend is to be observed for the frequency of occurrence of maritime air masses, even though there is a positive sign before the equation's vector (near zero tendency).

Spectral analysis of the course as smoothed by a 13-point moving average points to the presence of a wide-amplitude periodicity. The greatest values for the periodogram are shown at frequencies of 0.017606 (a period of 56.8 years), 0.021127 (47.3 years), 0.028169 (35.5 years) and 0.031690 (31.6 years), not including periodicity corresponding to half and a quarter of the length of the series. A clear peak on the figure for spectral density is generated by the 56.8- and 47.3-year periodicities. The course of raw (unfiltered) data features such a double peak with maximum periodicity of 59.2 and 42.3 years. It may thus be considered that the periodicities dominating are of c. 60 years (59–57) and of c. 42–47 years. There is no sign of any clearer occurrence of a periodicity of c. 100 years – as is characteristic of temperature change and described or referred to in numerous studies by Polish researchers.

A question emerges as to how probable the obtained results are, especially in relation to that part of the sequence that has be generated from Berlin data. A certain indication may here be gained by comparing the results obtained with those changes in the character of the circulation over areas nearby that have been determined using other methods. One such more reliable set of indicators registering the thermal nature of winters, and indirectly also atmospheric circulation, is that concerning the development of ice cover on the western Baltic.

Koslowski and Glaser (1999) analysed ice conditions over the western Baltic in the period 1500–1860, i.e. up to the time that instrument-based observations became widespread. They have been able to link up the periods in which the frequency of severe winters increases with a decrease in the intensity of zonal flow and an increase in the frequency of occurrence of blocking systems (and *vice versa* in the case of mild winters).

On this basis the authors in question have designated periods of the intensification of zonal (western) flow (identified with the increased intensity of action of the North Atlantic Oscillation in the period December to February), as well as periods of its clear weakening in winter (identified by a declining NAO index and the frequent occurrence of blocking). In the period under discussion here extending from the 18th to the 19th centuries, they determined the presence of successive periods of this kind: the years 1655–1710 (with a weakening of western flow), 1711–1762 (increased intensity), 1763–1860 (weakening, with the maximum frequency of occurrence of blocking in the years 1780–1820). Inevitably, there should be a certain relation between the periods of increase and decline in values for the winter NAO index and the frequency of occurrence of masses of maritime air over Poland (albeit one of limited strength due to the omission of the warm period of the year).

In comparing the aforementioned periods of rises and falls in the frequency of occurrence of masses of maritime air over Central and Northern Poland with the results of research by Koslowski and Glaser (1999), it proves possible to note certain common features, of which the most important is the concordance between the occurrence of an end to a period of intensive westernly flow (period

II) and the onset of a period of this flow being held back (1761–1762). As already mentioned, the designation of the onset of period II as presented in this paper (1725) is of limited precision and may presumably be located in the years 1711–1725, if the results of the analysis by Koslowski and Glaser are taken as a basis. This will be more realistic than the data adapted on the basis of nothing more than interpolation.

There will be no citing here of more detailed comparisons with widely-known works by Polish researchers on similar changes (also of temperature) that have occurred since instrument-based measurements began to be made on Polish territory (Boryczka et al. 1997, 1998; Kożuchowski and Marciniak 1986, 1989, 1991; Jokiel and Kożuchowski 1989; Kowalski 1992; Tamulewicz and Woś 1994; Trepińska 1973; Trepińska and Kowanetz 1997). In general it may be claimed that there is far-reaching concordance in the determination of the end of the 19th century as a period of clearly marked continentality of climate, the first three decades of the 20th century as a phase of increasing oceanity of climate (period V), and the subsequent reinstatement of increasing continentality (period VI) reaching a peak in the years 1940–1941. There is less agreement when it comes to the setting of limits between periods VI and VII, with a several-year difference being noted between the limits set by the authors and the results obtained by other workers.

It is obvious that the causes of change in the frequency of occurrence of maritime air masses should be sought in the action of a circulation factor. Apart from those mentioned in the literature, a factor modifying the atmospheric circulation over Central Europe, including Poland, is the thermal state of the North Atlantic, and specifically the distribution of temperature anomalies at its surface. The observed state, including also the thermal aspects identified for the 18th and 19th centuries and not discussed more fully here, would seem to correspond with the conclusions from Bjerknes (1965), regarding the character of the atmospheric and oceanic circulation in the period of the Little Ice Age and the consequences of the greater frequency of occurrence of a wave from the upper bays and gulfs of the Labrador Sea region and from across the Norwegian Sea, in conditions of a weakened Icelandic Low and consequent weakened northward transport of warmer Atlantic waters and cooling of the Norwegian Sea.

For the period of the last 28 years for which the necessarily precise data are available on the distribution of sea surface temperature in the North Atlantic, the ralations between anomalies of surface temperature and the nature of the circulation over Central and north-eastern Europe would seem to be a close one. In general, an increase in the temperature of the Sargasso Sea, and a decrease in the temperature within the cyclonal oceanic circulation of the North Atlantic, lead to a flow from the west of increased intensity, and thereby to a rise in the frequency of occurrence of maritime air masses over Poland. In recent years, following the greatest increase in the oceanity of the climate that has been observed in the last 120 years, changes in the distribution of anomalies in the North Atlantic have been of such a kind that they will increase the frequency of occurrence of a meridional form of circulation, and at the same time reduce the frequency of occurrence of masses of maritime air over Poland. This should entail a certain fall in the mean annual air temperature over the next 10 years, mainly as a result of a renewed decrease in mean temperatures in the autumn and winter months.

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