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INSTITUTE OF GEOGRAPHY AND SPATIAL ORGANIZATION

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70

GLOBAL CHANGE: POLISH PERSPECTIVES

4

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LESZEK STARKEL & MAŁGORZATA GUTRY-KORYCKA

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CONTENTS

Foreword 5
Kaczmarek Z., Liszewska M., Osuch M.: Water Management in South Asia in the 21st Century 7
Almabruk A.A.: Estimation of Evapotranspiration in Libya under the Impact of Plausible Global Climate Change 25
Trepińska J., Ustrnul Z., Kowanetz L.: Variability of the Air Temperature in Central Europe in the Years 1792–1995 43
Limanówka D.: Variablity of Selected Thermal Characteristics of the Air in the Carpathian Foothills in the Years 1951–1995 53
Cebulak E.: Variability of Precipitation in Selected Regions of the Carpathians in the Years 1951–1995 65
Twardosz R.: Long-term Variability in the Number of Days with Precipitation in Kraków in Relation to Circulation Patterns 77
Piotrowicz K.: Thermal Differentiation of Winters in the Carpathian Mountains Altitudinal Profile during the Period 1961/62–1990/91 89
Rakusa-Suszczewski S., Kidawa A.: Variability of the South Shetland Islands Geoecosystem 101

FOREWORD

This 4th issue in the series "Global Change — Polish Perspectives" concentrates on two aspects: assessment of the influence of global climate change on the water cycle at the lower latitudes exemplified by Asia and North Africa, and consideration of the trends noted for air temperature and atmospheric precipitation in southern Poland.

Z. Kaczmarek, M. Liszewska and **M. Osuch** outline the prospects for 21st century water management in southern Asia in the light of the emerging global warming. On the basis of a numerical simulation, the authors state that the four agricultural countries use 91 per cent of their water resources. The future uptake of, and requirements for, water are estimated in relation to anticipated global warming.

A. Ali Almabruk uses mathematical models (the Penmann Method and that of Budyko-Zubenok) in an effort to define the level of evapotranspiration in Libya, and pays attention to the possibility of increasing water deficit and irrigation needs as a result of probable global warming.

The second group of papers commences with an article from **J. Trepińska, Z. Ustrnul** and **L. Kowanetz** on variability in the air temperature in central Europe in the years 1791–1995, on the basis of the long and uniform measurement series from Kraków. The authors demonstrate clear regional trends to the changes, as well as the increasing warming role of urban areas (heat islands).

D. Limanówka considers the nature of trends for mean annual air temperature and long-term seasonal means for a parallel cross-section of the Carpathian Foothills in the years 1951–1995. It is shown that foothill areas with different dominant circulation patterns may react in different ways to global warming.

E. Cebulak is concerned with variability in the precipitation in selected regions of the Polish Carpathians in the years 1951–1995. She points to clear differences between the western and eastern parts of the chain where total precipitation and its seasonality are concerned, and these clearly correspond to the conclusions of D. Limanówka.

R. Twardosz analyses changes in the number of days with precipitation in Kraków, on the basis of the long observational series for the years 1814–1995. It is shown changes in atmospheric circulation influence the level of 24-hour precipitation, the number of days with precipitation and the frequency of occurence of catastrophic phenomena.

Finally, **K. Piotrowicz** analyses thermal changes in winters along an altitudinal cross-section of the Carpathians in the 30-year period 1961/62 –1990/91.

Changes in the high-mountain areas (> 1000 m a.s.l.) have occured with a certain delay, attesting to the greater thermal stability of advection masses of air untransformed by relief.

This series of 5 climatological articles attests to the temporal and spatial complexity of trends to the changes we must deal with in studies seeking to predict regional climatic change in the 21st century.

The volume is augumented by a paper from **S. Rakusa-Suszczewski** and **A. Kidawa**, who present the transformation of the geoecosystems of the South Shetlands (Antarctic) on the basis of 20 years of research carried out in the surroundings of Poland's Arctowski scientific station on King George Island. The research confirms the clear influence on the marine ecosystems of the Antarctic coast that increased temperature and a decline in glaciation have exerted in recent decades.

From the editorial board

GEOGRAPHIA POLONICA 70, 1997

WATER MANAGEMENT IN SOUTH ASIA IN THE 21ST CENTURY

ZDZISŁAW KACZMAREK, MAŁGORZATA LISZEWSKA, MARZENA OSUCH
Institute of Geophysics, Polish Academy of Sciences
ul. Księcia Janusza 64, 01-452 Warszawa, Poland

ABSTRACT: The paper presents the results of the impact of climate change on water resources in four countries in South Asia. Under present socio-economic and climatic conditions, China, India, Pakistan and South Korea are facing water deficits. The characteristic feature of water management in South Asia is the dominating role of agriculture in water use. The key question addressed in the paper is the impact of climate change on water resources, and the adaptive measures that may be used to cope with water deficits. In all the analyzed countries, the main reason for worsening water conditions is the expected population growth. The effect of climate change is in most cases marginal, independent of the scenario applied. Improved demand management and institutional adaptation are primary components in increasing the robustness of water systems in South Asia under increasing supply uncertainty due to demographic processes and climate change.

KEY WORDS: climate change; irrigation; water resources.

INTRODUCTION

In an earlier paper (Kaczmarek *et al.* 1995) we provided a preliminary evaluation for 26 countries in Europe and Asia of the possible joint implications of population growth and climate change on annual *per capita* water availability in the years 2020 and 2050. The key question addressed concerned the impact of expected climatic perturbations on regional *per capita* water supply, and the kind of adaptive measures which could be applied to cope with possible negative consequences of these perturbations. Three transient Global Circulation Models (GCMs) applied to assess changes in air temperature and precipitation patterns for the years 2020 and 2050 were those developed by:

(a) The Geophysical Fluid Dynamic Laboratory, Princeton (GFTR);
(b) The Hadley Centre, Bracknell (HCTR);
(c) The Max Planck Institute for Meteorology, Hamburg (MPTR).

The following general observations were made:

(a) Estimated future *per capita* water resources differ substantially among the three scenarios;

(b) In Asia, the population growth will be the decisive factor influencing future possibilities to meet water demands;

(c) In some regions climate change may cause an increase in available water resources, while in others it will lead to worsening of the water situation.

These conclusions were based on simple sensitivity analysis and should be considered a preliminary assessment. To assess the impact of climate change on the intraannual and interannual distribution of available water resources, complex models of hydrological processes were applied in the current study. Another feature of it is an attempt to appraise changes in water requirements due to demographic, economic and climatic processes. A comparison of water supply and demand will form a basis for conclusions concerning the future water situation, and for necessary management actions aimed at assuring the water needed for domestic use, food production, and other economic activities. Water can become a barrier to sustainable development due to a number of environmental and socio-economic factors among which only some depend on climate while others are subject to policy decisions which may help to adapt water systems to changes in atmospheric processes.

In this paper we concentrate on four countries in South Asia facing temporal water deficits under present socio-economic and climatic conditions: China, India, Pakistan and South Korea. As can be seen from Table 1, rapid population growth may lead to a dramatic reduction in *per capita* water availability. This would burden both individual households and all sectors of the national economies. In South Asia, irrigation is by far the largest water user, and, other things being equal, water diverted to other uses would depress agricultural production. The climate change issue adds a new dimension to this dilemma because irrigation water requirements may increase in a warmer climate.

TABLE 1. Population and *per capita* water availability in South Asia

Country	Year 1990		Year 2020		Year 2050	
	Pop (mln)	WR/cap	Pop (mln)	WR/cap	Pop (mln)	WR/cap
China	1,134	2,470	1,434	1,950	1,556	1,800
India	849	2,060	1,304	1,340	1,623	1,080
South Korea	43	1,460	52	1,210	54	1,170
Pakistan	112	2,660	225	1,320	316	940

Source: Fredericsen *et al.*, (1993).

WATER RESOURCE ASSESSMENT

Climatological and hydrological baseline data used in the current study were based on: (a) global climatic data sets from the National Centre for

Atmospheric Research in Boulder (U.S.A.), (b) data provided by the Global Runoff Data Centre in Koblenz (Germany), and (c) published sources on water resources assessment (Frederiksen *et al.* 1993; Shiklomanov 1996). Temperature and precipitation changes were based on the three transient GCMs referenced in the previous section.

There are several problems with using GCM data as inputs in hydrological assessment studies. Firstly, the spatial scale of current global atmospheric models is much coarser than required for water resources analysis. Secondly, regional climate estimates, particularly in the case of rainfall, are very uncertain. Therefore, for a water resources impact study several — all feasible — climate scenarios should be used, in order to assess the possible range in water supply and demand implications.

The incremental characteristics ΔT and rP were obtained from results of transient climate models predicted for year 2050 conditions, and then interpolated from a respective GCM grid to a grid assumed for a given country, with resolution depending on the country's size. (see e.g. Fig. 1). The usual procedure is to add expected differences ΔT to "historical" temperature data. Similarly, current precipitation data were multiplied by the ratios rP of GCM precipitation for future and current climates.

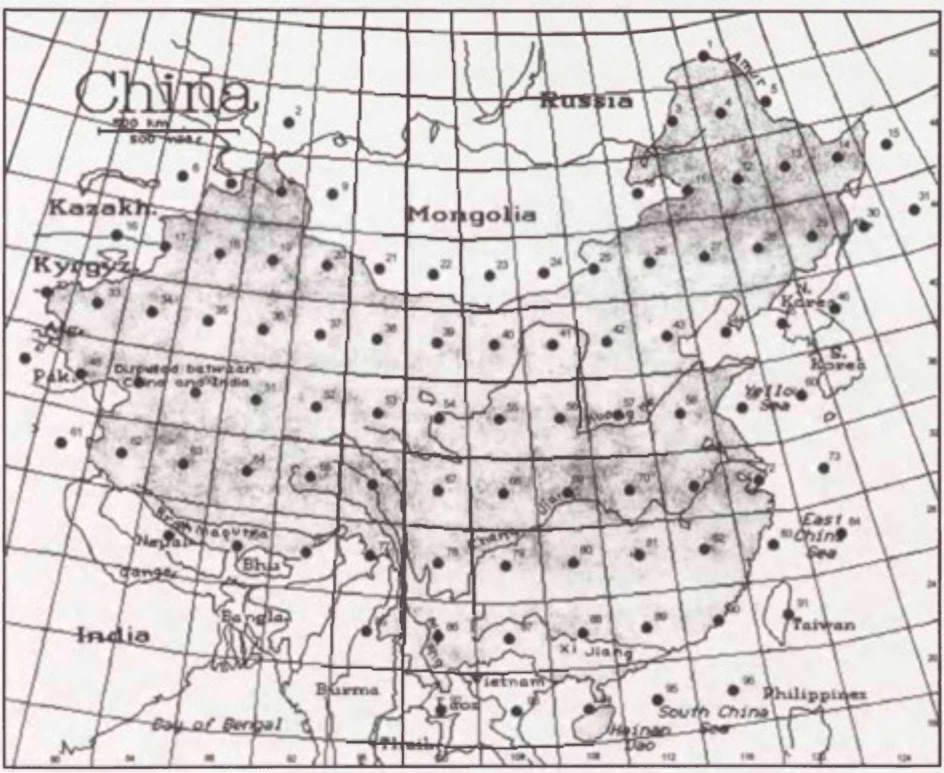

Fig. 1. Grid points in China

Methodological approaches for transferring climatic forcing to water balance characteristics vary widely. The key input variables to most of the hydrological models are catchment precipitation P and potential evapotranspiration PET, the latter being calculated from other meteorological variables. Because of limited access to data, the Thornthwaite method was used in this study (Thornthwaite, 1948), where PET was calculated based on air temperature only. To assess the impact of snow accumulation on precipitation, the P values for winter were transformed based on the mean monthly air temperature.

A conceptual hydrological model CLIRUN (Kaczmarek 1993) was applied to estimate water supply data. The model differs from previous approaches in two respects: (a) water balance components vary as continuous functions of time within assumed time intervals, e.g. months; (b) the stochastic properties of precipitation, evapotranspiration, runoff and catchment storage are expressed either in the form of simulated time series, or by a set of probabilistic matrices. The water balance equation has the form:

$$S_{\max}\frac{dz}{dt} = P - R_s - R_g - R_b - E \tag{1}$$

where relative catchment storage $z = S/S_{\max}$ is the ratio of actual storage to maximum catchment capacity. The immediate runoff R_s, delayed runoff R_g, and evapotranspiration E are conceptualized functions of storage, precipitation and potential evapotranspiration:

$$R_s = \varphi_1(z, P), \quad R_g = \varphi_2(z), \quad E = \varphi_3(z, PET) \tag{2}$$

Substituting into (1) one obtains:

$$S_{\max}\frac{dz}{dt} = \Phi(z, P, PET, R_b) \tag{3}$$

In the latest version of CLIRUN, the relation (3) has been assumed as:

$$\Phi(z, P, PET, R_b) =$$
$$= \frac{(1 - z^{\mu})P}{1 + \varepsilon - z^{\mu}} - z^2\left[\alpha - \frac{2}{3}PET\right] - \frac{5}{3}zPET - R_b \tag{4}$$

Hence, after integrating:

$$\int_{z_0}^{z_t}\frac{dz}{\Phi(z, P, PET, R_b)} = \frac{dt}{S_{\max}} \tag{5}$$

Solving equation (5) for given z_0, P, PET, and R_b one obtains:

$$z_t = \Phi(z_0, P, PET, R_b, S_{\max}, t) \tag{6}$$

For the next time interval z_t becomes z_0. Average values of water balance variables for the time interval <0, t> are (i = 1, 2, 3):

$$\bar{\varphi}_i(\ldots) = \frac{1}{t}\int_0^t \varphi_i(\ldots)\, dt \tag{7}$$

or after replacing *dt* by *dz*:

$$dt = S_{max} \frac{dz}{\Phi(z, P, PET, R_b)} \tag{8}$$

one gets:

$$\bar{\varphi}_i(\ldots) = \frac{S_{max}}{t} \int_{z_0}^{Z_t} \frac{\varphi_i(\ldots)}{\Phi(z, P, PET, R_b)} dz \tag{9}$$

Details of CLIRUN may be found in the cited paper. Computer programs for its various versions have been developed for IBM-compatible PCs. The model depends on three parameters, namely S_{max}, α, and ϵ, which should be determined by a calibration procedure, based on minimization of the mean square error of catchment outflows. Because a lack of reliable runoff data did not allow for the calibration of the water balance parameters for each grid cell in the analyzed countries, approximate relations between model parameters and the dryness index $w = P_{annual}/PET_{annual}$ were used:

$$\alpha = 1 - 0.6w + 0.1w^2,$$
$$\epsilon = 0.02w^3,$$
$$BF = 0.02P_{annual}, \tag{10}$$

where $w = P_{annual}/PET_{annual}$.

Other parameters were assumed to be constant values, namely catchment capacity S_{max} equal to 300 mm for lowlands and 200 mm for mountains, and $\mu = 0.5$. Finally, mean monthly runoff data were calculated based on mean monthly *P* and *PET* values, for each grid cell in China, India, South Korea and Pakistan. Figure 2 presents an example of changes in annual runoff for the GFTR scenario for China.

ESTIMATION OF WATER REQUIREMENTS

Most of the countries in South Asia have predominantly agricultural economies, with irrigation accounting for a high percentage of their water demand. Although the statistical data are not reliable it can be estimated that *per capita* water use for food production is about 350 m^3/year in China, 830 m^3/year in India, 290 m^3/year in South Korea, and 1,220 m^3/year in Pakistan. Of the four countries, that with the highest percentage of water use going to irrigation is Pakistan, with a figure of 98 percent. The lowest percentage is in South Korea where 75 percent of water use is for irrigation. The irrigated cropland area ranges from 0.03 ha/cap in Korea to 0.14 ha/cap in Pakistan.

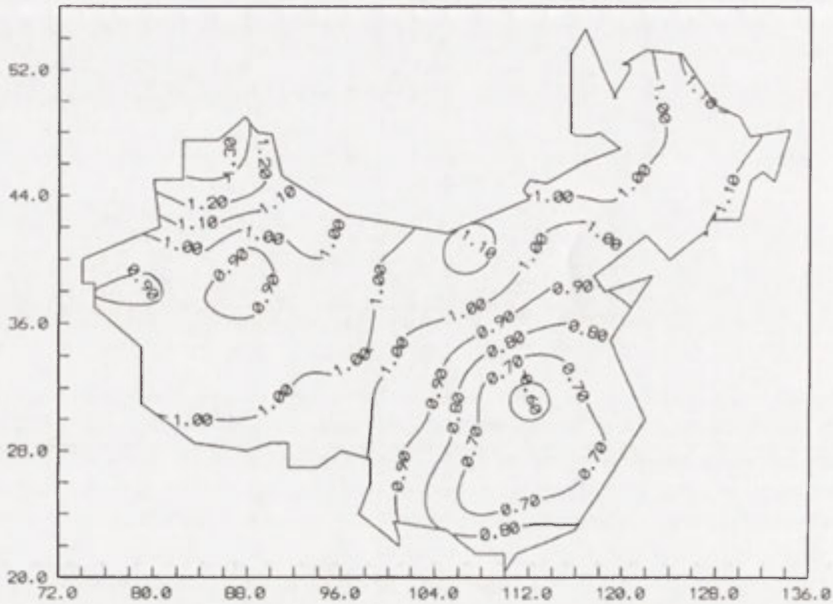

Fig. 2. Ratio of annual runoff for GFTR and present climates in China

In order to assess the irrigation water requirements for changed climatic conditions, the model CROPWAT developed at the Secretariat of FAO was used. Input data are monthly P and PET values, plus crop characteristics. Output is in the form of monthly and seasonal crop water requirements expressed in mm, where one mm corresponds to 10 m^3 per hectare of irrigated land. Water required for irrigation in a given country, for the assumed climate in the year 2050, was calculated by means of the formula:

$$WD_{irr} = N \cdot A_{irr} \cdot w \cdot r_{irr} \tag{11}$$

where:

N — denotes population,

A_{irr} — irrigated cropland [ha/cap],

w — amount of water actually used for irrigation [m^3/ha],

r_{irr} — the ratio of unit irrigation requirements for the 2050 climate scenario and actual climate.

Finally, each country's water demand for uses other than food production is added to the total demand calculated for irrigation. The actual water abstraction from monitored sources for domestic and industrial use in the four countries ranges from 31 m^3/cap-year in Pakistan to 62 m^3/cap-year in South Korea. This picture is probably blurred by the fact that water is also withdrawn from large number of local, mostly groundwater, intakes. For comparison, the current average standard for industrialized countries is

130 m^3/cap-year. In the calculations presented below we assume that by 2050, for China and South Korea, the demand for non-irrigation water will have risen to this standard level. For India and Pakistan we assume it rises to only 100 m^3/cap-year.

The final step is the assessment of water vulnerability in each of the four countries. In the 1995 paper we compared estimated resources to a uniform benchmark of 1000 m^3/cap-year — defining any country below that benchmark as experiencing chronic water scarcity (Engelman and LeRoy 1993). Such an indicator may be useful for comparison of the water situation in countries of similar climatic and economic conditions. It would, however, be difficult to use it in countries of which one depends highly on irrigation for food production, while the other is characterized by rain-fed agriculture. A more useful comparison is between estimated resources *WR* and estimated demand *WD*, and that is what is provided here. Each of the countries is classified among the following categories:

Water sufficiency:	Resources/Demands > 5,
Water stress:	3 < Resources/Demands < 5,
Water scarcity:	2 < Resources/Demands < 3,
Extreme water scarcity:	Resources/Demands < 2.

NATIONAL ASSESSMENTS

CHINA

90 per cent of the population lives in the eastern part of the country, from 100°E to 130°E, and that is where most of the country's economic activity takes place. It was therefore reasonable to focus the analysis of water resource problems in this part of China, which has an area of about 5.53 million km^2, and a 1990 population exceeding one billion people. Most of eastern China has favourable climatic conditions for agriculture production, rice in the south corn and wheat in the north. The irrigated area is about 47 million ha, equivalent to 48 per cent of total cropland.

Surface water resources formed in eastern China equal 1,600 km^3/year. In addition, about 300 km^3/year of Himalayan waters may be used to meet water demands in the Yangtze river basin. The average 1990 *per capita* water resources in eastern China equal 1,870 m^3/year, although they are unevenly distributed during the year. A high proportion of the rainfall occurs during the monsoon season, which lasts four to six months. Consequently, about 75 percent of river runoff in eastern China flows during the summer half-year when water is needed for irrigation. Changes in mean monthly *T* and *P* values, as predicted by the climate scenarios, were estimated for each grid cell. Average eastern--China annual values for temperature increment ΔT and precipitation ratio r_P, as well as the change in *PET* are shown in Table 2.

The monthly water balance constituents were calculated for each grid cell by means of the CLIRUN model for current climatic conditions and for the three climate scenarios. Results are summarized in Table 3, which shows calculated values for water resource characteristics in the investigated area (1.0 mm/day corresponds to 365,000 m^3/year–km^2), as well as expected changes in the year 2050 due to climate change predicted by the three scenarios.

Based on a World Bank report (Frederiksen *et al.* 1993), the current average water withdrawal from the territory of eastern China may be estimated as 450 km^3/year, from which 400 km^3 is used in the agriculture sector. The rest, equal to about 50 m^3/cap-year meets domestic and industrial water demands. The CROPWAT model was then applied to calculate current irrigation water demands under the three GCM scenarios. These values

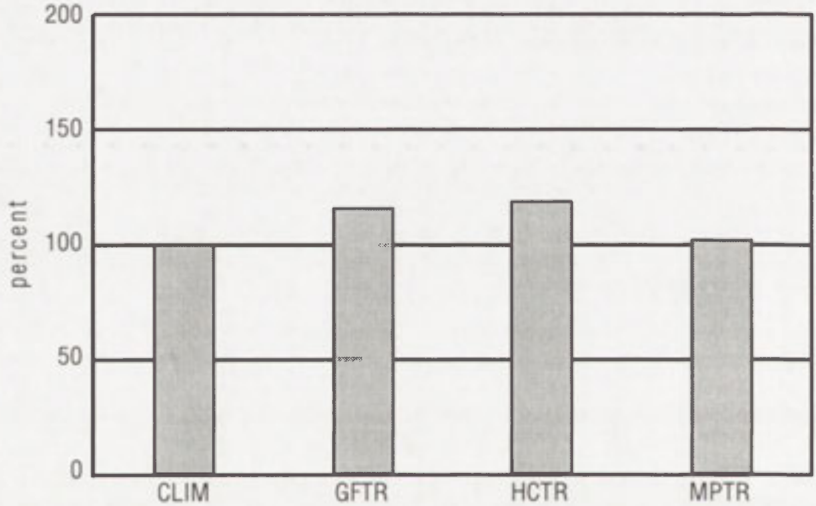

Fig. 3. Ratio (%) of irrigation water demand (m^3/ha, seasons) for climate scenarios in eastern China

were then adjusted to take into account various water losses in the irrigation systems. The ratio of future irrigation demand to current irrigation demand, r_{irr}, is shown in Figure 3 for each of the three scenarios. In order to estimate future water demands in the agriculture sector it was assumed that the present level of 0.046 ha of irrigated area *per capita* should be used in calculating demands up to the year 2050.

Finally, projected water demand for non-irrigation uses, calculated as described above, was added to projected irrigation demand and compared to the total water resources. The results are presented in Table 4.

TABLE 2. Climate change scenarios for the year 2050 in eastern China

Variable	Units	GFTR	HCTR	MPTR
$T_{SCE} — T_{CLI}$	°C	2.0	3.7	1.0
P_{SCE}/P_{CLI}	%	103	117	115
PET_{SCE}/PET_{CLI}	%	111	121	104

TABLE 3. Changes in runoff characteristics in eastern China for three climate scenarios

Variable	Present climate mm/day	Change in % GFTR	Change in % HCTR	Change in % MPTR
$R_{January–December}$	0.747	–20	+4	0
$R_{April–September}$	1.070	–20	+6	–2
$R_{monthly\ minimum}$	0.256	–22	–15	–2

TABLE 4. Water resources (WR) and water demands (WD) in eastern China during the summer period, for various climatic conditions

Year	Climate	WR km^3	WD km^3	WR/WD	Water availability
1990	present	1,390	427	3.25	stress
2050	present	1,390	624	2.23	scarcity
	GFTR	1,110	707	1.57	extreme scarcity
	HCTR	1,450	746	1.94	extreme scarcity
	MPTR	1,390	635	2.19	scarcity

INDIA

The country has an area of 3 287 000 km^2, and an average population density of 258 people per km^2. Water resources formed in Indian territory equal approximately 1,460 km^3, and an additional 580 km^3/year flows into India from neighbouring countries. Most runoff occurs during the monsoon season from June to September. India has favourable climate conditions for agriculture production, mostly rice, corn, wheat and cotton. In 1990 India's irrigated cropland covered about 56 million ha, equivalent to 33.1 percent of total cropland. The *per capita* irrigated area works out at 0.066 ha. Assuming that no more than 50 percent of external inflow can be used effectively in meeting water demands, average water availability is estimated to be 2,060 m^3/cap.

For CLIRUN calculations, India is divided into grid cells with a resolution of 2° by 2°. The resulting country-wide average values of ΔT, r_P, and r_{PET} calculated for the three GCM scenarios are given in Table 5. It is important to note that the Hadley Centre transient scenario predicts an unrealistic precipitation increase. We therefore do not include the Hadley Centre results in the final comparison of water supply and demand projections for India shown in Table 7.

TABLE 5. Climate change scenarios for the year 2050 in India

Variable	Units	GFTR	HCTR	MPTR
$T_{SCE} - T_{CLI}$	°C	1.6	2.4	1.2
P_{SCE}/P_{CLI}	%	115	184 ?	105
PET_{SCE}/PET_{CLI}	%	126	139	115

Runoff was calculated for the current climatic conditions, and for the three climate scenarios. Simulation results are summarized in Table 6 [(1.0 mm/day corresponds to 365,000 m^3/(year, km^2)]. Because the runoff increase for the HCTR model seems to be misleading, it was decided to exclude this scenario from analysis concerning the water situation in India.

The 1990 annual water withdrawal in India is estimated to be 380 km^3, of which 93 percent is used for irrigation. To estimate future agricultural water demand, the CROPWAT model was used with input data (precipitation and potential evapotranspiration) for the actual climate, and for the 2050 climate predicted by three transient scenarios. Fig. 4 shows significant impact for both GFTR and MPTR scenarios. It was assumed that the present index

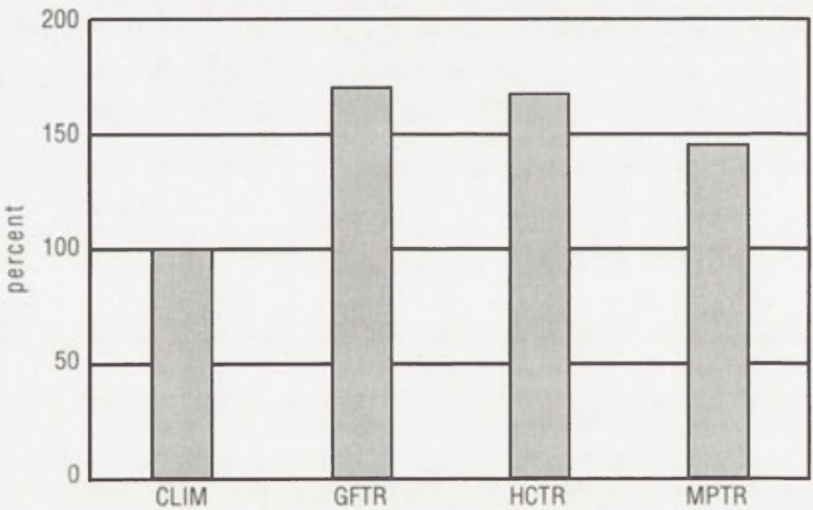

Fig. 4. Ratio values (%) of irrigation water demand (m^3/ha, seasons) for climate scenarios in India

of 0.066 hectare of irrigated cropland *per capita* will not be changed until the middle of next century. Table 7 shows the overall results once non-agricultural water demands are added at the projected level of 100 m^3/cap-year. In calculating *WR* values it was assumed that water resources flowing into India from other countries change in response to climate change by the same percentage as the water resources originating in India.

The overall conclusion is that future water crises in India seem inevitable. The principal cause remains population growth. The impact of climate change on the *WR*/*WD* ratio is not significant in the case of the GFTR scenario. But it may be critical if, as predicted by the MPTR scenario, the expected temperature increase is accompanied by only a small change in summer rainfall.

TABLE 6. Changes in runoff characteristics in India for three climate scenarios

Variable	Present climate mm/day	Change in % GFTR	Change in % HCTR	Change in % MPTR
$R_{January–December}$	0.994	+29	+296 ?	+8
$R_{April–September}$	1.572	+61	+359 ?	+8
$R_{monthly\ minimum}$	0.115	−18	0	−16

TABLE 7. Water resources (WR) and water demands (WD) in India during the summer period, for various climatic conditions

Year	Climate	WR km^3	WD km^3	WR/WD	Water availability
1990	present	1,400	366	3.82	stress
2050	present	1,400	757	1.85	extreme scarcity
	GFTR	2,250	1,291	1.74	extreme scarcity
	MPTR	1,510	1,108	1.36	extreme scarcity

SOUTH KOREA

South Korea is one of the most developed economies in Asia. It has an area of 98,700 km^2 and a high population density of 440 inhabitants per km^2 in 1990. However, its projected population increase is significantly lower than in the region as a whole. Industry plays an important role in the national economy, but agriculture retains a relatively high share of economic activity, reflecting the government's policy of domestic self-sufficiency in food. Like other south Asian countries, South Korea has favourable climate conditions for agriculture and the irrigated share of total cropland is very high at 56 percent. Water resources are formed predominantly on the country's own territory, with negligible external inflow.

Current climatic data and expected changes of T and P were estimated for each grid cell based on global data sets for the three transient scenarios. Table 8 presents the country-wide average mean annual characteristics for temperature increments, rainfall ratio and *PET* ratio calculated for South Korea from the GCMs. Runoff values calculated by CLIRUN for the present climatic conditions, and for assumed scenarios, are given in Table 9.

The current water use in South Korea is estimated at 10.7 km^3, of which 75% is used by agriculture, 11% in domestic demand, and 14% by industry. CROPWAT results for irrigation demand are presented in Figure 5, and

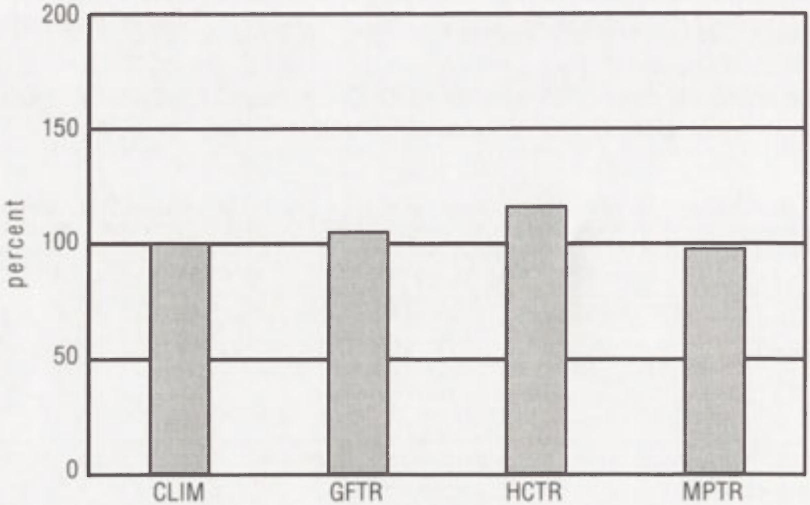

Fig. 5. Ratio values (%) of irrigation water demand (m^3/ha, seasons) for climate scenarios in South Korea

Table 10 shows the overall results once non-irrigation water demands are added at the projected level of 130 m^3/cap-year. The general conclusion is that the ratio of water resources to demand in South Korea is worse in 2050 than in 1990, but the contribution of climate change to this result seems to be negligible.

TABLE 8. Climate change scenarios for the year 2050 in South Korea

Variable	Units	GFTR	HCTR	MPTR
$T_{SCE} - T_{CLI}$	°C	1.9	3.5	0.6
P_{SCE}/P_{CLI}	%	109	108	111
PET_{SCE}/PET_{CLI}	%	111	123	103

TABLE 9. Changes in runoff characteristics in South Korea for three climate scenarios

Variable	Present climate mm/day	Change in % GFTR	Change in % HCTR	Change in % MPTR
$R_{January-December}$	1.859	+7	–2	+18
$R_{April-September}$	2.210	+16	+2	+10
$R_{monthly\ minimum}$	1.034	–13	–34	+7

TABLE 10. Water resources (WR) and water demands (WD) in South Korea during the summer period, for various climatic conditions

Year	Climate	WR km^3	WD km^3	WR/WD	Water availability
1990	present	37.4	9.4	3.98	stress
2050	present	37.4	13.6	2.75	scarcity
	GFTR	43.4	14.2	3.06	stress
	HCTR	38.1	15.5	2.46	scarcity
	MPTR	41.1	13.4	3.07	stress

PAKISTAN

Much of Pakistan is arid or semi-arid. Runoff generated within the country supplies only half of the needs of its huge irrigation systems in the middle and lower parts of the Indus river catchment. Pakistan relies heavily on water "imported" from neighbouring countries, particularly India, a continuing source of potential conflict. Pakistan's area is 771,000 km^2, and its population density 190 people per km^2. The population is projected to almost treble by 2050. Food production depends on irrigation: currently 77 percent of available cropland is irrigated, equivalent to 0.14 hectare of irrigated land per person.

Table 11 presents the country-wide average values for ΔT, r_P, and r_{PET} calculated for Pakistan from the GCM models. Runoff values calculated by CLIRUN are given in Table 12. As noted above, much of Pakistan's water comes from the Himalayas where changes in runoff may differ from those

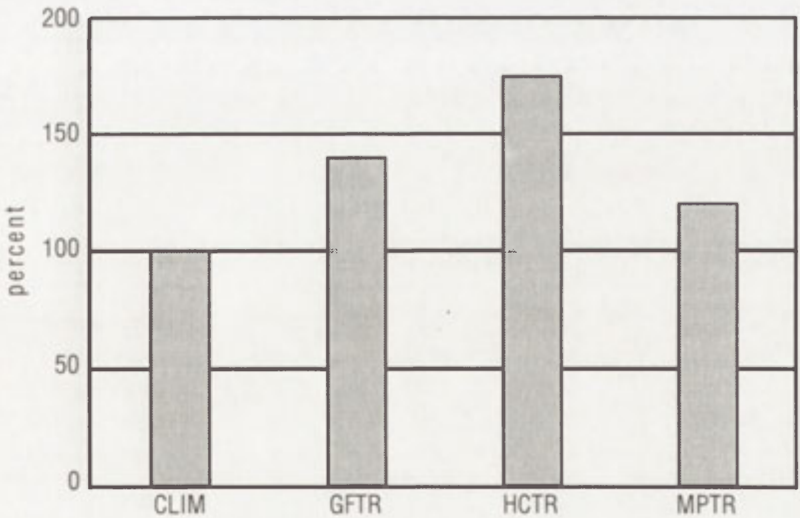

Fig. 6. Ratio values (%) of irrigation water demand (m^3/ha, seasons) for climate scenarios in Pakistan

estimated for the dry internal territory of Pakistan. Changes in Himalayan runoff were therefore taken from the calculations done for the grid cells for northern India. The overall large increase in annual runoff confirms opinions expressed in the literature (see Arnell et al., 1996; Kaczmarek *et al.* 1996) that arid zones are more sensitive to climate change than humid catchments.

According to the World Bank estimates (Frederiksen *et al.* 1993), the 1990 annual water withdrawal in Pakistan was 153.4 km^3 per year, of which 98 percent went for irrigation — the highest figure in Asia. CROPWAT results for irrigation demand are presented in Figure 6, and Table 13 shows the overall results once non-irrigation water demands are added at the projected level of 100 m^3/cap-year. As noted earlier, we have assumed no additional irrigated land in 2050 in Pakistan due to limited land availability. Because population continues to grow, this implies a substantial decrease in the *per capita* irrigated area in Pakistan from the present 0.14 hectare to about 0.06 hectares.

TABLE 11. Climate change scenarios for the year 2050 in Pakistan

Variable	Units	GFTR	HCTR	MPTR
$T_{SCE} - T_{CLI}$	°C	1.7	3.3	1.6
P_{SCE}/P_{CLI}	%	131	126	105
PET_{SCE}/PET_{CLI}	%	126	146	119

TABLE 12. Changes in runoff characteristics in Pakistan for three climate scenarios

Variable	Present climate mm/day	Change in % GFTR	Change in % HCTR	Change in % MPTR
$R_{January-December}$	0.291	+115	+92	–8
$R_{April-September}$	0.364	+160	+150	–21
$R_{monthly\ minimum}$	0.093	–42	–34	–23

TABLE 13. Water resources (WR) and water demands (WD) in Pakistan during the summer period, for various climatic conditions

Year	Climate	WR km^3	WD km^3	WR/WD	Water availability
	present	157	151	1.04	extreme scarcity
2050	present	157	208	0.76	extreme scarcity
	GFTR	314	292	1.07	extreme scarcity
	HCTR	291	366	0.80	extreme scarcity
	MPTR	138	247	0.56	extreme scarcity

As can be seen from Table 12, water availability is a critical barrier to Pakistan's development with food production, public health and economic development — all being at high risk. This conclusion is driven mainly by continuing population growth despite limited water supplies even today. It is largely independent of future climate change, although the MPTR scenario suggests a particularly problematical future. The implication for Pakistan is simply that top priority must continue to be given to increasing the efficiency of water use as quickly and extensively as possible.

CONCLUSIONS

Calculations presented here for China, India, South Korea and Pakistan indicate that all four countries may face serious difficulties over the next century in their efforts to guarantee reliable supplies of water. The main reasons for expected water crisis are elaborated briefly in the next two paragraphs. They are increasing population, a significant dependence on irrigated agriculture in meeting food demand and difficulties in generating the financial resources to invest in additional storage reservoirs and other measures to expand available water resources. Competition among agriculture, industry and cities for limited water supplies is already constraining development efforts in south Asian countries.

In countries with mostly rain-fed agriculture, climate is the principal factor in shaping water quantity and its temporal distribution, while population and industrial development are the main influences on water demand. In South Asia, dependence on irrigated agriculture is a serious issue because water demands for irrigation are more affected by climate change than non-irrigation water demands, as can be learned from data presented in Figures 3 to 6. The combined effect of decreased supply and increased water demand may lead to extremely difficult water problems, as for example in the MPTR scenario for Pakistan.

The ratio *WR*/*WD* was used in this study as a synthetic index of the water situation in the years 1990 and 2050. The importance of population growth is shown in Figure 7, which presents a summary of joint possible impacts of population density and climate change on the ratio of water resources to water demand. Except in the case of Pakistan, the principal cause of worsening water supply conditions is clearly population growth. This is a robust conclusion in that it is independent of the GCM scenario used.

There are considerable differences in estimating changes in hydrological processes between climate scenarios and in some cases global atmospheric models fail in reproducing the actual climate. Similar discrepancies characterize irrigation water requirements estimated by means of the CROPWAT model. Consequently, the predicted changes in water supply and demand are uncertain. An extreme case is a very poor simulation, by the Hadley Centre model, of rainfall fields in the Indian sub-continent.

It is not possible to recommend specific adaptation measures based on the country-scale analyses presented here. Changes in climatic and hydrological characteristics will vary over the territory of large countries and policy decisions depend on local hydrological conditions, economic conditions and national priorities. Therefore, at this stage only general concepts concerning possible policy action can be formulated, based on opinions reflected in recent IPCC reports (Arnell *et al.* 1996; Kaczmarek *et al.* 1996).

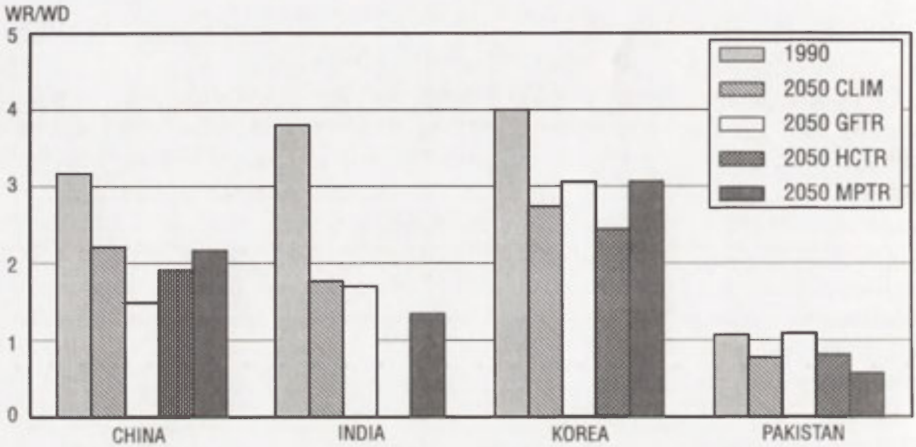

Fig. 7. Ratio of water supply to demand values for actual climate and three transient scenarios

A long-term strategy requires that a series of plausible development scenarios be formulated based on combinations of population growth and climate change assumptions along with economic, social and environmental objectives (Carter *et al.* 1994). After these scenarios are established, taking into account the possibility of climate change, a set of alternative long-term strategies for water management may be formulated that consist of different water management measures, policy instruments or institutional changes, which are designed to meet best the objectives of a particular growth and development scenario. An overview of water supply and demand management options was presented by Frederick (1994) as a part of an attempt to develop approaches to dealing with increasing water scarcity. The range of response strategies should be compared and appraised, each with different levels of costs, environmental and socioeconomic impacts. Some will be better suited to dealing with climate change uncertainty — i.e. more robust and resilient, others will focus on environmental sustainability. Some are likely to emphasize reliability of supply. The reality is that, after application of engineering design criteria to various alternatives, the selection of an "optimal" path is a decision based on social preferences and political realities.

Regions that have little or no control of natural flows and are largely dependent on precipitation, must implement a different set of water management strategies to those in river basins with a high degree of control in the form of reservoirs, canals, levees etc. Similarly, rapidly-urbanizing areas in South Korea will require different responses to agricultural regions in Pakistan. In China and India, there will be increasing pressures to expand the cropland base and to retain the existing level of *per capita* irrigated area. This will require the mobilization of additional water. On the other hand, in Pakistan, where much of the country is arid and semi-arid, and irrigation is essential for crop production in most areas, there is little possibility to expand the irrigated area over the present level of 77 percent of the total cropland. To address increasing food demand due to population growth, the only solution for Pakistan is to improve irrigation efficiency through drip irrigation systems and other water-conserving technologies. Pricing to encourage efficient water use in agriculture seems to be inevitable in most of the South Asian countries. The general policy conclusion continues to be one promoting "minimum regret" strategies. That is, population growth alone argues that high priority be given to strategies to improve water management. These are also the strategies that promise to best prepare countries for the still highly uncertain impacts of future climate change.

Based on the above considerations, the following final conclusions seem to be justified:

(a) The characteristic feature of the water resources situation in South Asia is the dominating role of the agriculture sector in water use. For the four countries, the average share of agriculture in the total water withdrawal is 91 per cent, the highest value for any of the world's regions. This is the reason for the high vulnerability of the region's water management to climate change;

(b) Although non-climatic factors dominate in shaping the future water situation in South Asia, there are reasons for water resource decisionmakers to be concerned, because both the water supply and demand may be affected by climate change;

(c) The unit *per hectare* and total irrigation water requirements may significantly increase; water resource strategies should not overlook technological solutions where these can bring in more rational use of water in agriculture;

(d) The rationalization of water use and improved demand management and institutional adaptation are primary components for increasing the robustness of water resource systems under increasing supply — and — demand uncertainty due to climate change;

(e) The current generation of climate models do not offer the requisite degree of region-specific information on future climate; this requires continuous adaptation of design criteria, development plans, operating rules and water-allocation policies to the newly-developed climate scenarios.

Research should continue in order to improve predictions and permit the evaluation of specific adaptive responses in particular river basins and in important economic sub-regions in South Asia. More — detailed assessments of climate change impacts on branches of water management other than irrigation, such as hydropower and water supply for megacities — also deserve additional research attention.

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ESTIMATION OF EVAPOTRANSPIRATION IN LIBYA UNDER THE IMPACT OF PLAUSIBLE GLOBAL CLIMATE CHANGE

ALMABRUK A. ALI[1]

Institute of Geophysics, Polish Academy of Sciences
ul. Księcia Janusza 64, 01-452 Warszawa, Poland

ABSTRACT: The effects of global warming on reference evapotranspiration are investigated and discussed in this report. There are numerous methods for estimating evapotranspiration in the literature. However, we chose to use two acceptable methods for an arid climate: the "Penman method" proposed by the Food and Agriculture Organisation of the United Nations (FAO), and the second one after Budyko-Zubenok, for the purpose of comparison.

The amount of water needed for agriculture with and without climate change is estimated and discussed. A computer program based on Penman's method is used, with the necessary data, provided by a separate computer program. To compare results of different models, two climate scenarios were used in these analyses. The results show that the evapotranspiration will increase from north to south, due to an increase in temperature which is the result of the increase in the content of CO_2, as well as of other greenhouse gases in the Earth's atmosphere.

KEY WORDS: water scarcity, climate change, evapotranspiration, Libyan case study.

INTRODUCTION

In modern times, all nations do their best to achieve the maximum possible production, particularly in the field of agriculture, considering that this is the pillar of industry and the basic constituent of life. Therefore, self-sufficiency in foodstuff production is the ultimate objective of most nations, in order that they might not fall prey to economic pressure and thus maintain full independence. Studying present and future evapotranspiration is this very important to estimate irrigation water requirements, because agriculture in an arid country is the biggest consumer of water.

Libya is located in the northern part of Africa, as shown in Figure 1. The climate is extremely arid, arid or semi-arid. The country is large (1,750,000 km^2), but only 21 percent of the area is suitable for agriculture production. The precipitation is not well distributed over the country so

[1] On leave from Al-Fateh University, Faculty of Engineering, Tripoli, Libya.

irrigation is not dependent upon it. All agricultural lands are irrigated, the water supply for the irrigation is coming solely from groundwater.

Libya's demand for water has increased exponentially due to a high rate of population increase and greater irrigation activity resulting from land reclamation projects. In one lifetime between 1950 and 1990, Libya's population increased from 1.1 to 4.5 million. Simultaneously, *per capita* use of water had increase from 400 to 1260 cubic meter per year for agriculture only (World Bank 1994). As a result of these two trends, the overall use of water increased more than three times in that half century. The problem is really complex, because our demand is greater than available natural water resources.

Fig. 1. Geographical location of Libya

The aim of this report is to look critically into the existing problems of water shortage, high population growth, industrial development and often unwise water resource management and expected global warming. In short, the expected impact of global climate change will be acute in different aspects of our life direct or indirect. We hope that this work will be a meaningful contribution to our understanding of expected climate change impacts in the present and future, especially for crop water requirements.

A further aim of this report is to introduce information to our planning engineers and decisionmakers at all levels of government. We also encourage our researchers and scientists to examine the implications of climate change for long-term policies in different fields, such as: water resources, electricity demand, sea level rise, forestry, air quality, human health, urban infrastructure, etc.

BACKGROUND ON CLIMATE CHANGE

During the first century of the industrial revolution, CO_2 concentration rose from about 50 parts per million (ppm) to reach 316 ppm in 1959. Since 1959 it has risen another 30 ppm. It is estimated that the current level will have doubled by the middle of the 21st century (Kirshen and Fennessey 1992; Fennessey and Kirshen 1992).

The important change currently in prospect is global warming due to man's emission of greenhouse gases such as carbon dioxide, methane, ozone, CFCs (Chlorofluorocarbons), nitrous oxide, etc. Their effect is to increase the intensity of the exchange of long wave radiation between the earth's surface and the lower atmosphere. Such a change will have immediate consequences through raising the near-surface temperature and indirect consequences on rainfall, evaporation and the whole hydrological cycle. It may also have indirect effects acting via ecosystem changes. The effects of warming on crop water requirements will be discussed in this report.

The United Nations Intergovernmental Panel on Climate Change estimated that, under a "business as usual" scenario, global mean temperature would be expected to rise by 0.3°C per decade. This would result in a 1.2°C increase in global mean temperature by around the year 2030, taking it to a level higher than at any time in human history. The rate of change in temperature is very high, and will probably be too fast for natural and human systems to adapt.

Some twenty scenarios, based on different global circulation simulation exercises, point to a possible increase of (3± 1.5)°C in the temperature of the lower atmosphere towards the middle of the next century. This is the case if, as feared, the CO_2 level in the atmosphere doubles to 700 ppm, as compared to the present level of 360 ppm (Waggoner 1990). It must be borne in mind, however, that these are only scenarios, and that, although based on the best data available, they are still only possibilities and in no way represent a prediction, still less a forecast. Fundamental uncertainties remain concerning a number of basic modelling parameters such as heat exchanges between the oceans and atmosphere.

In this report we use the results of two general circulation models, namely those of the Geophysical Fluid Dynamics Laboratory (GFDL) and Goddard Institute for Space Studies (GISS). The GCM results should not be considered predictions, but plausible scenarios of future climate change. In this analysis we assume that temperature increase has a linear trend. These two models show respectively that the current temperature can increase on average by 1.8 and 2.1°C by the year 2030; this increase is applicable for Libya. This high temperature will certainly affect crop water requirements since evaporation will increase. Therefore, more water will be needed for agriculture in the future.

Present and expected evapotranspiration in the future (year 2030) is discussed and estimated in this report. We choose the following scenarios:

— present temperature and precipitation,
— expected temperature and same (present) precipitation.

In estimating the impact of climate change on water demand, we choose to introduce climate change scenarios. Climate scenario is a feasible, internally-consistent description of a possible future climate. It is not a forecast, nor indeed a prediction. Its purpose is to guide high-level policy rather than to initiate a practical response such as the construction of an engineering scheme. Climate change impact studies are driven by estimates of changes based on climate change scenarios, and commonly use a range of alternative scenarios (Vijay, 1996).

Three basic methods have been used in creating climate change scenarios, namely:

— *Temporal analogues,* an approach assuming that the future will be like some defined period in the past.

— *Spatial analogues,* an approach assuming that the future climate of one region can be represented by the current climate of a second region.

— *Climate model simulations,* the majority of studies of climate change impact, have used scenarios based on the output from general circulation models (GCMs). However, it is not possible to use the output from a GCM directly in a hydrological impact study, for a few reasons, among them the large area required for the implementation of such a model. Therefore, several methods have been proposed to express GCM output at a scale and in a form suitable for hydrological impact studies.

We use the output of two models (GISS and GFDL). Generally, scientists assume that current trends in emissions will continue and that climate will change gradually over the next century. Thus, the purpose of this work is to calculate evapotranspiration and crop water requirement, with and without climate changes.

METHODOLOGY

Evapotranspiration, Et_o, is the sum of the water used by plants in a given area and the water evaporated from surrounded soil in that area in any specified time (Maidment 1992). It is a key factor for estimating irrigation water requirements. Rational evaluation of that factor is essential at planning, designing, operating and managing levels in water resource projects, particularly under arid conditions which prevail in many parts of the country (Salih and Sendil 1984). Under these conditions, water is a precious commodity of limited quantity and is obtained, in most cases, from non-renewable groundwater storage.

The allocation of this type of water to current and anticipated future uses (i.e. agricultural, industrial, domestic, etc.) should be achieved through reliable methods of evaluation, if future disappointments are to be avoided. Most important is the agricultural allocation (80–87%), which usually demands the largest share of that water as well as giving difficulty in abolishing agricultural schemes once they are established.

Several empirical methods have been selected from the literature (Kaczmarek, Krasuski 1991). These methods are used in estimating reference evapotranspiration under arid conditions.

Direct measurements are the most favourable source of information when available but unfortunately they are scarce in many arid areas (case study). Four direct methods are available in the literature (Chow *et al.* 1988; Reddy 1986) for direct measurement of evapotranspiration, namely:

— the water budget method,

— field experimental plots,

— soil moisture depletion studies,

— the lysimeter method.

Prediction of evapotranspiration is usually achieved through empirical formulae built on climatic observations (i.e. Penman, Blaney-Criddle, Budyko--Zubenok, etc.), when direct measurements are not available.

Two standard evaporation rates are defined, potential evaporation and reference crop evaporation, and these are used as the basis for evaporation estimates. These rates are conceptual in the sense that they represent idealised situations. Potential evaporation, E_p, is defined as "the quantity of water evaporated per unit area, per unit time from an idealised, extensive free water surface under existing atmosphere conditions", (Chow *et al.* 1988). In turn, reference crop evaporation, E_{cr}, is "the rate of evaporation from an idealised grass crop with a fixed crop height of 0.12 m, an albedo of 0.23, and a surface resistance of 69 s/m", (Maidment 1992). Evapotranspiration tends to increase with the increase in temperature, sunshine and speed of the wind and with the decrease of humidity.

SELECTION OF ESTIMATION METHODS

From the numerous methods reported in the literature, the criterion adopted in this work for choosing suitable methods for estimating reference evapotranspiration was based on the "Penman method". The Budyko-Zubenok method was used for comparison of results. Furthermore, we chose these two methods for the following reasons:

— the necessary data are available;

— the "Penman method " has been adopted by the Food and Agriculture Organisation of the United Nations;

— the two methods are recommended and advocated by many scientists worldwide.

The results of the analysis showed that there is no big difference between the "Penman" and "Budyko" methods, therefore all the calculations of irrigation water requirements are based on Penman, because it is the most widely-known method. The following information is required for the Penman method:

— basic information on the climate station are: station name, altitude latitude and longitude.

— monthly climatic data: temperature, relative humidity, sunshine and wind speed.

The selected catchments are the Tripoli, Benghazi (Benina) and Kufera regions, with full climatic observation stations, whose location and length of obtained records are summarised in Table 1. Typical mean values for the observed climatic factors of air temperature, relative air humidity, wind speed, sunshine and precipitation are shown in Tables 2, 3 and 4 for the three selected regions respectively.

TABLE 1. List of the data used

Station	φ	λ	Observation period	T (years)
Air temperature				
Tripoli	32.9N	13.2E	1944–1995	51
Benina	32.1N	20.3E	1945–1995	50
Kufera	24.2N	23.3E	1951–1995	44
Precipitation				
Tripoli	32.9N	13.2E	1931–1992	61
Benina	32.1N	20.3E	1946–1991	45
Kufera	24.2N	23.3E	1951–1991	40
R. air humidity				
Tripoli	32.9N	13.2E	1944–1991	47
Benina	32.1N	20.3E	1945–1990	45
Kufera	24.2N	23.3E	1951–1991	40
Sunshine				
Tripoli	32.9N	13.2E	1961–1994	33
Benina	32.1N	20.3E	1963–1994	31
Kufera	24.2N	23.3E	1975–1994	19
Wind speed				
Tripoli	32.9N	13.2E	1949–1994	45
Benina	32.1N	20.3E	1949–1994	45
Kufera	24.2N	23.3E	1974–1994	20

THE PENMAN METHOD

Penman et al., recommended this equation for estimating potential evaporation E_p (in mm/day)

$$E_p = \frac{\Delta}{\Delta + \gamma}(R_n + A_h) + \frac{\gamma}{\Delta + \gamma}\,\frac{6.43(1 + 0.536\,U_2)\,D}{\lambda} \quad (1)$$

where:

R_n — net radiation exchange for the free water surface, mm/day,

A_h — energy advocated to the water body, mm/day,
U_2 — wind speed measured at 2 m, m/sec.,
D — vapour pressure deficit $(e_s - e)$, kPa.

$$\Delta = \frac{4098e}{(237.3 + T)^2} \tag{2}$$

$$\lambda = 2.501 – 0.002361\, T_s \quad \text{MJkg} \tag{3}$$

$$\gamma = 0.0016286 \frac{P}{\lambda} \quad \text{kPa} \tag{4}$$

$$e_s = 0.6108 \exp\left(17.27 \frac{T}{273.3 + T}\right) \quad \text{kPa} \tag{5}$$

where e_s is a saturated vapour.
The equation for estimating reference crop evaporation, in mm/day; is:

$$E_{rc} = \frac{\Delta}{\Delta + \gamma^*}(R_n - G) + \frac{\gamma}{\Delta + \gamma^*}\frac{900}{T + 275}U_2 D \tag{6}$$

where:
R_n — is net radiation exchange for the crop cover, mm/day,
G — measured or estimated soil flux, mm/day,
T — temperature in degrees Celsius,
γ^* — $\gamma(1 + 0.33U_2)$.

THE BUDYKO-ZUBENOK METHOD

Budyko-Zubenok introduced the following method to calculate the mean monthly rate of potential evapotranspiration (Kaczmarek and Krasuski 1991).

$$PET = 86400 \frac{0.622\rho}{P\rho_\omega} D\,[e_s(Tw) - e]\,, \quad (\text{mm day}^{-1}) \tag{7}$$

where:
ρ — 1.293 (kg m^{-3}),
ρ_w — 1000 (kg m^{-3}),
p — is the air pressure in hPa,
D — 3.0 (mm s^{-1}) during the cold part of the year,
D — 6.0 (mm s^{-1}) at high air temperature.

Zubenok observed that in arid regions D may 10 mm s^{-1}. In order to obtain a continuous relation between D and T, and taking into account the dependence of D on the level of catchment aridity, the following heuristic rules are proposed:
If $T < 0$, then $D = 6.0 + 0.3T$
If $T > 0$, then $D = 5.2 + (349 + 70\,P_a) / T_a$

where:

T_a is the annual value for mean air temperature,

P_a is the annual value for precipitation.

Budyko proposed calculating the saturated vapour $e_s\,(Tw)$ by an approximate formula

$$e_s(Tw) = 6.11\exp\left(\frac{17.27Tw}{237.2 + Tw}\right) + 0.09\,(T_{max} - T_{min})^2\,\frac{d^2e_s(Tw)}{d^2Tw} \tag{8}$$

where T_{max} and T_{min} are mean monthly extreme temperature values. The second part of the right side of the equation presents a correcting factor aimed at eliminating the error caused by calculating es (Tw) based on mean monthly values of Tw. The second order derivative in the equation may be replaced by an approximate relation:

$$\frac{d^2e_s(Tw)}{d^2Tw} = 0.029 + 0.0025Tw\,, \quad (0 \le Tw \le 25) \tag{9}$$

The parameter Tw in the Budyko-Zubenok method would be an apparent land surface temperature, where the catchment were to be supplied with an unlimited amount of water. To find its numerical value, the energy balance equation:

$$Q_{sr}\,(1 - alb) + Q_{lr} - G - \frac{0.622\rho L}{1000p}\,D\,[e_s(Tw) - e] - \frac{\rho C_p}{1000}\,D(Tw - T) = 0 \tag{10}$$

has to be solved for Tw.

L is the latent heat of vaporisation equal to 2 470 000 (J kg^{-1}),

C_p = 1005 (J kg^{-1} deg^{-1}) is the specific heat of dry air, G(W m^{-2}) is the energy flux between surface and soil, and other elements were defined earlier.

For the long wave radiation balance in the equation, the slightly modified Brunt formula may be used:

$$Q_{lr} = 5.5 * 10^{-8}\,[0.552\,e^{1/7}\,(T + 273.2)^4 - (Tw + 273.2)^4](0.2 + 0.8n_s) \tag{11}$$

where n_s is the monthly relative sunshine duration. For calculating G we use the Albrecht formula:

$$G = 0.001\varphi_L[Q_{sr}(1 - alb) + Q_{lr}]_{max}\,\sin\left[\frac{\pi}{6}\,(Mo - Mo_{max} + 4)\right] \tag{12}$$

TABLE 2. Current climate and expected climate in the year 2030: the Tripoli Region (a), the Benghazi Region (b), the Kufera Region (c)

Month	Obser. temp. in 0°C	Exp. temp. in 0°C (2030) GISS	Exp. temp. in 0°C (2030) GFDL	Obs. R.H. %	Obs. W.S. m/sec.	Obs. Sunsh. h/day	Obs. ppt. mm/m.	Calc. Poten. evapot. mm/d 1995	Exp. Poten. evapot. mm/d 2030 GFDL	Exp. Poten. evapot. mm/d 2030 GISS
					a. the Tripoli Region					
Jan.	12.0	13.6	13.8	69.6	3.62	6.09	57.6	1.9	2.1	2.1
Feb.	13.2	15.2	15.7	65.5	3.49	7.09	36.8	2.5	2.8	2.8
Mar.	15.2	16.5	17.5	63.9	3.77	7.75	26.8	3.3	3.6	3.7
Apr.	18.6	20.1	21.3	58.8	4.19	8.61	15.0	4.6	4.9	5.1
May	22.4	24.1	24.7	53.7	4.28	9.80	4.3	6.1	6.4	6.6
Jun.	26.0	28.2	28.3	51.6	4.29	10.8	0.0	7.2	7.7	7.7
Jul.	27.1	29.1	29.1	55.0	3.69	12.1	0.0	7.1	7.6	7.6
Aug.	27.9	29.9	30.1	56.6	3.61	11.5	0.0	6.8	7.2	7.2
Sep.	26.3	28.1	28.3	60.7	3.67	9.21	11.8	5.5	5.9	5.9
Oct.	22.4	24.2	24.3	64.4	3.32	7.55	36.5	3.9	4.2	4.3
Nov.	17.4	19.3	19.2	66.5	3.13	6.65	41.9	2.7	2.9	2.9
Dec.	13.4	15.5	15.3	69.1	3.44	5.77	58.6	2.0	2.2	2.2
					b. the Benghazi Region					
Jan.	12.5	13.9	13.9	76.4	4.63	5.85	67.5	1.9	2.0	2.0
Feb.	13.1	15.1	15.3	72.6	4.91	6.64	38.6	2.5	2.7	2.7
Mar.	15.0	17.1	17.2	67.1	5.40	7.63	25.8	3.5	3.8	3.8
Apr.	18.8	20.6	21.2	57.9	5.78	8.61	6.6	5.2	5.5	5.6
May	22.6	24.3	25.0	54.1	5.6	10.0	4.6	6.6	7.0	7.1
Jun.	25.5	27.5	27.5	54.6	5.42	11.3	0.0	7.4	7.9	7.9
Jul.	25.6	27.6	27.7	64.2	5.46	12.1	0.0	6.8	7.3	7.3
Aug.	26.5	28.4	28.4	65.0	5.08	11.6	0.0	6.5	7.0	6.9
Sep.	25.1	26.5	27.4	63.8	4.64	9.81	3.0	5.1	5.9	6.0
Oct.	22.5	24.4	24.4	64.5	4.7	8.36	20.7	4.5	4.7	4.8
Nov.	18.1	19.9	19.8	68.7	4.53	6.95	33.8	3.1	3.3	3.3
Dec.	14.2	16.4	15.8	74.0	4.63	5.58	67.0	2.1	2.3	2.3
					c. the Kufera Region					
Jan.	12.9	14.31	15.01	57.7	3.02	8.54	–	2.9	3.0	3.0
Feb.	15.3	17.13	17.72	52.9	3.33	9.02	–	3.7	4.0	3.0
Mar.	19.4	21.43	21.86	48.0	3.85	8.53	–	5.1	5.4	5.5
Apr.	24.7	25.57	26.31	42.0	4.12	9.13	–	6.9	7.1	7.3
May	28.4	30.62	31.64	39.3	4.23	9.65	–	8.3	8.7	8.9
Jun.	30.8	32.59	33.13	36.7	3.48	10.42	–	8.5	8.9	9.0
Jul.	30.6	32.26	32.49	41.5	3.41	11.63	–	8.4	8.7	8.9
Aug.	30.5	32.58	31.72	43.7	3.03	11.42	–	7.8	8.2	8.1
Sep.	28.4	29.89	30.68	46.0	3.08	9.79	–	6.8	6.9	7.2
Oct.	24.3	26.38	26.98	52.7	3.05	9.07	–	5.2	5.5	5.6
Nov.	18.4	20.06	21.22	57.2	3.03	8.89	–	3.8	4.0	4.1
Dec.	14.3	16.06	17.42	58.1	2.80	8.33	–	2.9	3.1	3.2

TABLE 3. Water required and to be required for the winter season in the Tripoli Region (a, b) , for the summer season in the Tripoli Region (c). for the Kharph season in the Tripoli Region (d)

Crop	Required Water[1] (mm) 1995	Water[2] increment (%) GFDL 2030	Water[3] increment (%) GISS 2030	Planning month
a. the winter season in the Tripoli Region				
Alfalfa	1503.8	8.29	9.6	Mar.
Citrus	843.8	8.70	10.61	Nov.
Grass	1342.4	8.44	9.78	Mar.
Date palm	1025.8	8.37	9.78	Oct.
b. the winter season in the Tripoli Region				
Onion	112.4	22.69	24.73	Oct.
Wheat	78.5	28.79	29.68	Oct.
Barley	65.9	31.71	32.93	Oct.
Potato	80.4	28.23	29.23	Oct.
Vegetables	71.8	22.7	23.88	Oct.
Pepper	81.8	27.14	28.24	Oct.
Tomato	119.2	22.48	23.99	Oct.
c. the summer season in the Tripoli Region				
Watermelon	545.2	7.4	9.08	Mar.
Onion	687.7	7.27	9.04	Mar.
Pepper	564.2	7.55	9.87	Mar.
Tomato	711.4	7.31	9.28	Mar.
Grape	697.7	7.14	8.5	Mar.
Potato	604.3	7.51	9.75	Mar.
Vegetables	382.8	5.88	9.59	Mar.
d. the Kharph season in the Tripoli Region				
Potato	268.5	10.91	12.1	Aug.
Tomato	290.4	11.26	12.9	Aug.
Onion	260.3	11.86	12.78	Aug.
Pepper	283.6	10.86	11.78	Aug.
Vegetables	312.8	8.95	9.94	Aug.

[1] Amount of water required (in mm) in current climate 1995
[2] Water increment (%) due to expected changes in global temperature, GFDL, 2030
[3] Water increment (%) due to expected changes in global temperature, GISS, 2030

TABLE 4. Water required and to be required for all-year crops in the Benghazi (Benina) Region (a), water required and to be required for the winter season in the Benghazi (Benina) Region (b), for the summer season in the Benghazi (Benina) Region (c), for the Kharph season in the Benghazi (Benina) Region (d)

Crop	Required Water[1] (mm) 1995	Water[2] increment (%) GFDL 2030	Water[3] increment (%) GISS 2030	Planning month
a. the Benghazi (Benina) Region				
Alfalfa	1574.3	8.47	9.10	Mar.
Citrus	912.7	8.27	8.95	Mar.
Grass	1409.9	8.56	9.20	Mar
Date palm	1094.4	8.50	9.16	Oct.
b. the winter season in the Benghazi (Benina) Region				
Onion	128.3	14.11	14.65	Oct.
Wheat	81.7	20.69	21.30	Oct.
Barley	67.1	24.74	25.34	Oct.
Potato	85.0	20.59	21.18	Oct.
Vegetables	86.8	16.01	16.94	Oct.
c. the summer season in the Benghazi (Benina) Region				
Watermelon	737.1	7.03	7.71	Mar.
Onion	726.8	7.09	7.76	Mar.
Pepper	613.7	6.97	7.87	Mar.
Tomato	757.5	7.00	7.74	Mar.
Grape	725.8	7.66	8.09	Mar.
Potato	655.5	6.90	7.81	Mar.
Vegetables	425.1	7.01	8.42	Mar.
d. the Kharph season in the Benghazi (Benina) Region				
Potato	318.5	10.24	11.62	Aug.
Tomato	335.2	11.07	12.30	Aug.
Onion	303.0.	11.19	12.50	Aug.
Pepper	328.4	10.81	12.10	Aug.
Vegetables	355.7	10.04	11.50	Aug.

[1] Amount of water required (in mm) in current climate 1995
[2] Water increment (%) due to expected changes in global temperature, GFDL, 2030
[3] Water increment (%) due to expected changes in global temperature, GISS, 2030

DATA

The data used in this study are of two types. The first ones are present-day data consisting of monthly and annual mean air temperature, precipitation, relative humidity, wind speed and sunshine duration records for individual stations, selected for the coastal belt and southern parts of Libya. The second type of data are: expected temperature in year 2030 with the other parameters kept constant.

Table 1 describes selected stations by latitude φ, and longitude λ, given in decimal degrees, as well as by the number of years of observation. Tables 2a-c show the observed temperature, relative humidity, wind speed, sunshine and precipitation for the regions of Tripoli, Benghazi and Kufera. Based on this data current and expected (for the year 2030) evapotranspiration is calculated.

We have adopted the hypothesis that the temperature will increase in a linear trend, around 1.8°C and 2.1°C by the year 2030, as a result of the increase of CO_2 in the atmosphere. This prediction is based on the results of the GISS and GFDL models respectively. The present analysis went through the following steps:

(a) In the first step, it was necessary to calculate evapotranspiration by the Budyko method;

(b) or to use the CROPWAT software package introduced by the FAO which is doing the same by the Penman method;

(c) next, the crop water requirements should be calculated on the basis of calculated evapotranspiration in point (a) or (b) for the present climate as well as the expected one.

Crop water requirements are defined here as "the depth of water needed to meet the water loss, through evapotranspiration, of a disease free crop, growing in large fields, under non-restricting soil conditions, including soil water and fertility, and achieving full production potential under the given growing environment" (Doorenbos *et al.* 1992).

RESULTS

The results, presented in the above Figure 2, show the expected annual increase in temperature, according to general circulation models. This increase is 1.8 and 2.1°C, according to the GFDL and GISS models respectively. It will be the main factor increasing evapotranspiration in the Tripoli, Benghazi and Kufera regions.

The computed monthly values, obtained from the two methods, at each station, have been fed into a computer to calculate the amount of water required and to be required for each crop in the three selected regions. Tables 3 and 4 show the water required and to be required for crops irrigated in, four different seasons, namely; all the year, the winter season, the summer season and the Kharph (autumn) season, in the selected regions of Tripoli and Benghazi.

In the Kufera region the computed monthly values (evapotranspiration, sunshine, wind speed, humidity and temperature) obtained from the different selected methods have been fed into the computer to calculate irrigation water requirements with and without climate change for each crops and season.

It is interesting to see that the percentage increment in water required and to be required as shown in Tables 5a-d for the Kufera regions will be less than in to other regions (Tripoli and Benghazi), in the summer season, but the requirement will be greater because of high temperature and type of soil. This trend is understandable, since, for the same crop, more water is needed if it is to be planted in Kufera region.

A summary of water increments (%) for the Tripoli and Benghazi regions is given in Table 6a. Furthermore, water increments (%) for the Kufera region are indicated in Table 6b.

It appears that water requirements will be higher in summer and in southern parts than in winter and northern coastal parts. Furthermore, the percentage increment in water requirements due to expected climate change will be a dependent variable. This increment will depend on the type of crop, season of the year and the place where it will be grown. The percentage increment is almost the same in each season in the Tripoli and Benina regions.

After these analyses, one can conclude that the evapotranspiration will increase from north to south. It will also increase due to temperature changes, because of the effects on Earth's atmosphere of CO_2 and other greenhouse gases.

Based on the analysis of crop water requirements using different scenarios, we can conclude that the percentage increment due to expected global warming, according to the GFDL and GISS models, for Kufera, is the following:

a) Using the GFDL model:
- 4.4% for crops irrigated all seasons of the year,
- 5.6% for crops irrigated in the winter season,
- 4.5% for crops irrigated in the summer season,
- 4.2% for crops irrigated in the Kharph season;

b) Using the GISS model:
- 6.3% for crops irrigated all seasons of the year,
- 7.2% for crops irrigated in the winter season,
- 6.6% for crops irrigated in the summer season,
- 6.5% for crops irrigated in the Kharph season.

Furthermore, we calculated water requirements for now and the future using the GISS model. The results made nearly the same predictions for both the Tripoli and Benghazi regions for which the percentage increment for the crops irrigated all year is 8.5%, for winter 24.35 %, for summer 7.5% and for the Kharph season 10.1%.

Making use of the GFDL model, for the same regions, the expected increment in water requirements for the four seasons is given as 8.5% for all-year irrigation, 24.4% for winter only, 7.5% for summer only, and 10% for Kharph irrigation only.

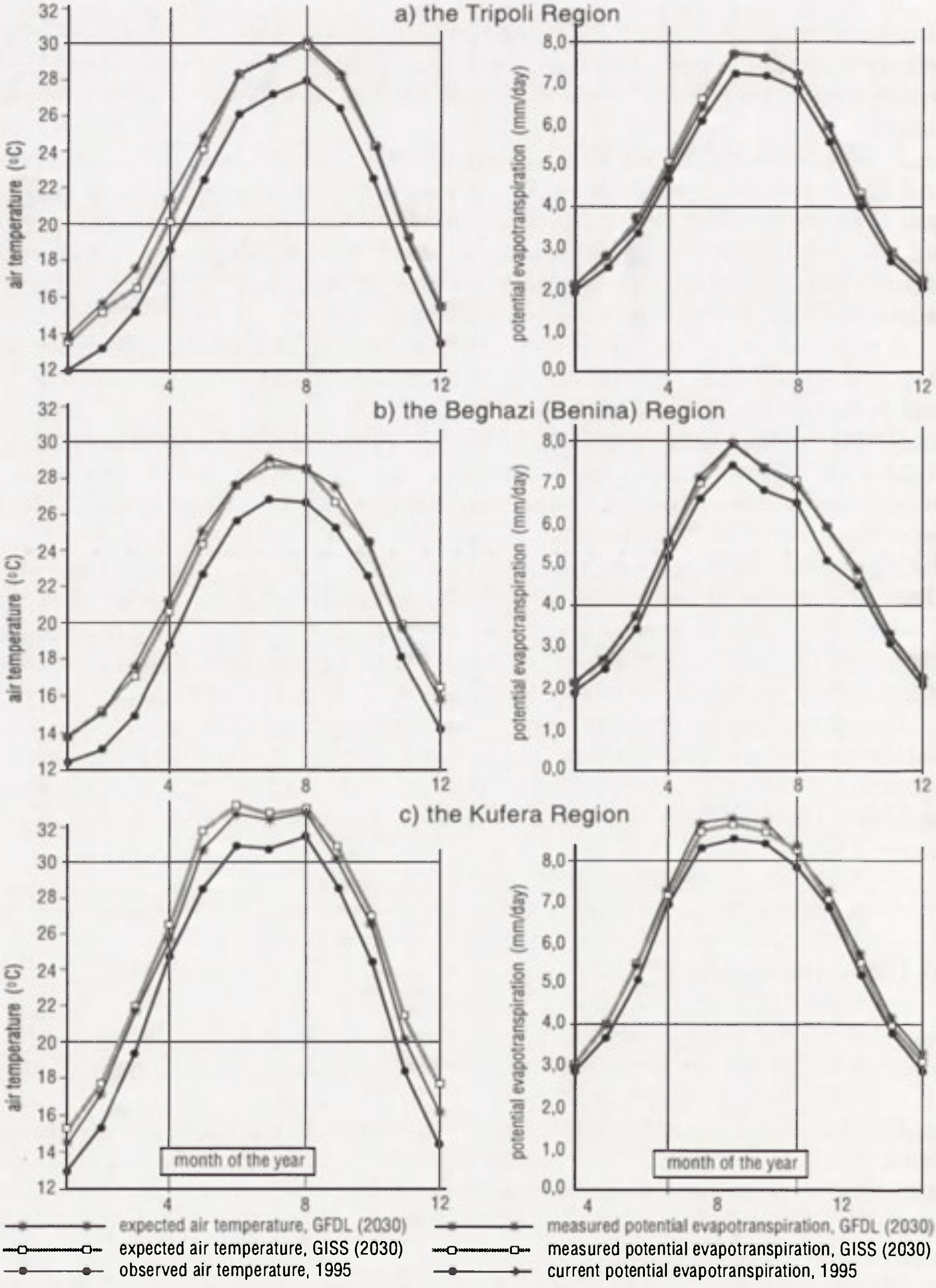

Fig. 2. Current (1995) and expected (according to the GFDL and GISS models) temperatures and potential evapotraspiration in the Tripoli (a), the Benghazi (b) and the Kufera (c) Regions

TABLE 5. Water required and to be required for all-year crops in the Kufera Region (a), water required and to be required for the winter season in the Kufera Region (b), for the summer season in the Kufera Region (c), for the Kharph season in the Kufera Region (d)

Crop	Required Water[1] (mm) 1995	Water[2] increment (%) GFDL 2030	Water[3] increment (%) GISS 2030	Planning month
		a. the Kufera Region		
Alfalfa	2322.5	4.43	6.28	Mar.
Citrus	1446.1	4.46	5.56	Nov.
Grass	2111.3	4.44	6.29	Mar.
Date palm	1689.1	4.43	6.28	Oct.
		b. for the winter season in the Kufera Region		
Onion	462.5	5.51	7.05	Oct.
Wheat	386.8	8.97	6.59	Oct.
Barley	374.9	5.20	6.62	Oct.
Potato	389.05	5.24	6.74	Oct.
Vegetables	298.0	4.70	7.18	Oct.
		c. for the summer season in the Kufera Region		
Watermelon	964.2	4.27	6.33	Mar.
Onion	958.7	4.54	6.56	Mar.
Tomato	995.6	4.37	6.42	Mar.
Grape	957.7	4.22	5.96	Mar.
Potato	868.1	4.35	6.47	Mar.
Vegetables	608.9	4.45	6.75	Mar.
		d. for the Kharph season in the Kufera Region		
Potato	570.9	4.35	5.51	Aug.
Tomato	595.8	4.43	6.95	Aug.
Onion	570.9	4.24	6.69	Aug.
Pepper	539.9	4.45	7.08	Aug.
Vegetables	493.3	4.00	4.38	Aug.

[1] Amount of water required (in mm) in current climate 1995
[2] Water increment (%) due to expected changes in global air temperature, GFDL, 2030
[3] Water increment (%) due to expected changes in global air temperature, GISS, 2030

TABLE 6. Percentage increment in the Tripoli and Benghazi Region (a), in the Kufera Region (b)

Season	Percentage water increment according to the GFDL model 2030	Percentage water increment according to the GISS model 2030
	a. the Tripoli and Benghazi Region	
All-year crops	8.50	8.93
Winter	24.35	22.30
Summer	7.50	9.45
Kharph	10.10	9.72
	b. the Kufera Region	
All-year crops	4.42	6.28
Winter	5.60	7.18
Summer	4.50	6.56
Kharph	4.24	6.50

SUMMARY

The expected climate change will in future create serious problems for Libya with regard to agricultural water demands. Evapotranspiration will increase due to the increase in temperature. As a result, this global warming will affect the water requirements for crops, because we need more water for agricultural production.

Estimating evapotranspiration is an obligatory step preceding the design and construction of any agriculture projects, especially in an arid climate. The average annual evaporation in the current climate in the coastal parts is 1560 mm/year, while in the south (oases) it is more than 40 per cent higher. Moreover, the average annual evaporation due to expected global climate change in the coastal belt will be 1820 mm/year. On the other hand, it will be higher in the oases in the southern parts of the country. In the oases, we expect an increment in evaporation of 27.5 per cent more than in the coastal regions. It must be born in mind, however, that these figures for crop water requirements represent the water needed to meet the loss through evapotranspiration.

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VARIABILITY OF THE AIR TEMPERATURE IN CENTRAL EUROPE IN THE YEARS 1792–1995

JANINA TREPIŃSKA[1], ZBIGNIEW USTRNUL[2], LESZEK KOWANETZ[1]
[1] Institute of Geography, Jagellonian University
ul. Grodzka 64, 31-044 Kraków, Poland

[2] Institute of Meteorology and Water Management
ul. Piotra Borowego 14, 31-215 Kraków, Poland

ABSTRACT: Use was made of the longest-existing series of air temperature observations from Central Europe, specifically those for Warsaw, Kraków, Prague and Vienna. It was, above all, the course of mean annual values for air temperature that was analyzed, thus allowing this study to serve also as a basis for further, more precise studies including the variability and cyclicity of air temperature values in particular months. The application and attempted interpretation of periodograms drawn up on the basis of data for January, April, July and October has confirmed the above opinion. In general, considerable concurrence in the courses of mean air temperature values at the selected stations may be noted, and hence the influence of the same circulation mechanisms shaping air temperature over a large area during the two centuries.

KEY WORDS: long air temperature series, mean annual air temperature, variability, periodicity.

THE OLDEST METEOROLOGICAL STATIONS IN CENTRAL EUROPE

There are not many meteorological stations in Europe that were established in the 18th century and have been operating daily until now. To be included among the oldest stations with homogeneous series of air temperature measurements are those of Warsaw, Prague, Vienna and Kraków. Concluded only recently were calculations and studies aimed at the utilization of the oldest part of the Kraków series, from 1792–1825. This work has inspired the present paper and the period taken into account is obviously related to the length of the Kraków observation series.

The exploitation of long measurement series requires knowledge about a station, methods of measurement and observation times and assurances as to a station's permanent location. These are the factors that guarantee the congeneric measurements termed metadata in recent scientific literature.

The selection of stations for the present work was based on a recognition that series of average monthly values for air temperature from these stations were as far as possible homogeneous. Both locations and observation times were proven, verified and corrected. Several earlier studies, even from the 19th century, were based on the same series and are regarded as truthworthy from the point of view of correctness.

The beginnings of air temperature measurements in Warsaw date back to the years 1779–1799. They were made on the Royal Castle terrace by the priest Karol Bystrzycki, astronomer to King Stanisław August Poniatowski. After a 3-year pause (for which missing data have been reproduced on the basis of the Vilnius series) observations were continued during the period 1803–1823 by a secondary school teacher, A. Magier, by the house wall on Piwna street. From November 1825 onwards, continuous meteorological observations began at the Astronomical Observatory on Aleje Ujazdowskie. These series are considered dependable. The homogeneity of all three Warsaw series of average monthly values for air temperature was established as early as in the 19th century. The authors involved in this work were W. Jastrzębowski, J. Kowalczyk and W. Gorczyński (Mietelski 1997). The third of these authors presented a series in the form of a table (Gorczyński 1916). The Warsaw observations were interrupted by war action in 1944, but were later completed in accordance with data from other Warsaw stations. This series is recognized as fulfilling the requirements of homogeneity.

The observations of air temperature in Prague were begun as early as in 1752 by the director of the Klementinum Jesuit College, the astronomer and physisist J. Stepling. Observations have been continuous since 1775 at a meteorological station by the wall of Klementinum, incorporated later into the Karol University. High scientific standard and continuity of observation were secured by the third director of the Klementinum College, A. Strnado. During the 19th century the Prague meteorological station maintained its very high standard, being a model for other similar stations (Pejml 1975, Mietelski 1997). At present, the station is staffed by personnel of the Hydrological and Meteorological Institute (H.M.U.). The site of measurements is well-evidenced in registers and may be considered to fulfil the basic requirements for series homogeneity. For this reason, the Prague series has been used frequently as a source for studies on climate change.

Meteorological observations in Vienna have been carried out since 1775 by staff members at the University Astronomical Observatory. In addition, it is known that air temperature values were noted even earlier, in the years 1734–1773 at the Vienna Jesuit College. The series from 1775 is most often used in studies devoted to climate change. Data were collected at the Wien Hohe Warte Station, located on the south-eastern slope of the Vienna Woods, in a sparsely build-up area. Air temperature was measured in a box close to the north wall of the house during the years 1873–1953. The whole series was calculated to the same terms with account taken of the differences in the locations of the close measurement points. More details of how this

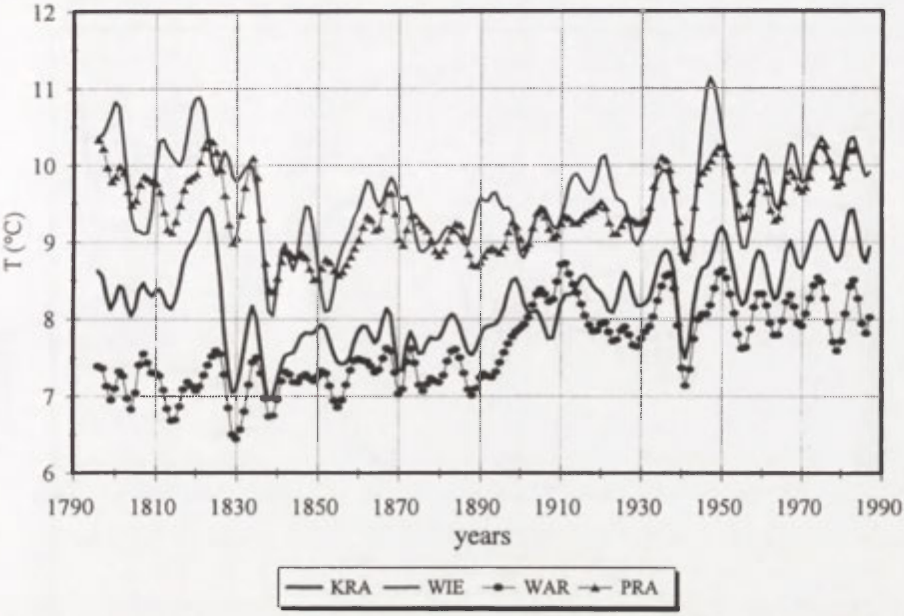


Fig. 1. Course of average annual air temperature at the different stations — data smoothed by 9-year Gauss filter (KRA — Krakow, WIE — Vienna, WAR — Warsaw, PRA — Prague)

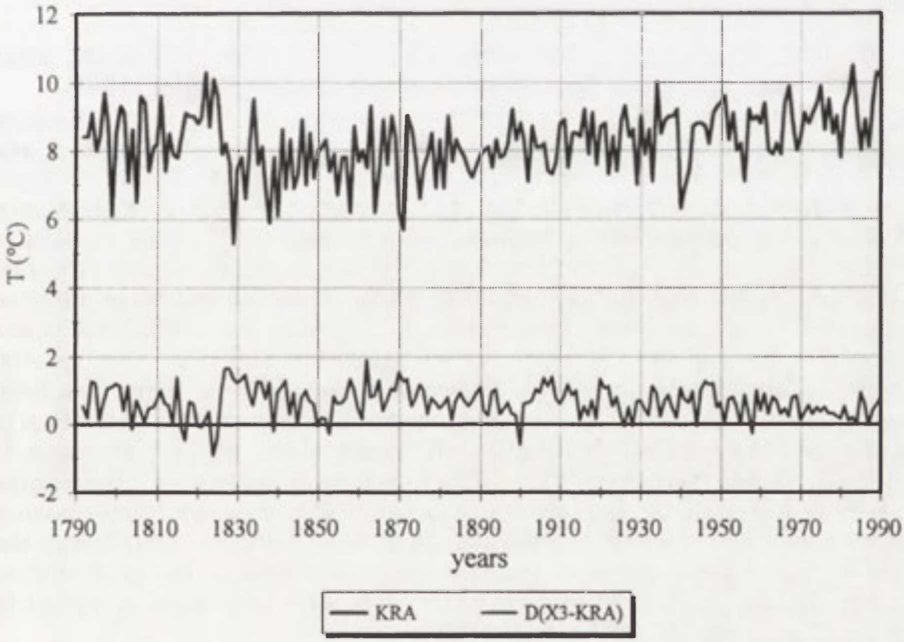


Fig. 2. Variability in average annual air temperature in Krakow (KRA) and course of average annual air temperature deviations from analogous values of the areal average calculated from 3 stations: Vienna, Warsaw and Prague {D(X3-KRA)}

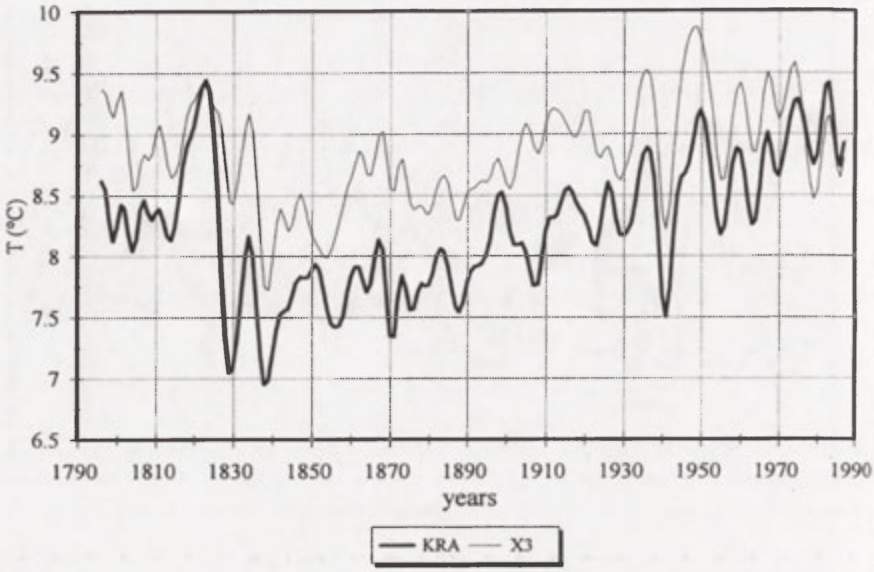


Fig. 3. Course of mean annual air temperature in Kraków (KRA) and mean annual areal values from the three meteorological stations (Warsaw, Prague, Vienna, X3) according to 9-year Gauss filter, 1792–1991

was done are presented in the work of R. Bohm (1992) and in the atlas entitled "Klima von Wien" by I. Auer, R. Bohm and H. Mohnl (1989).

The Astronomical Observatory of the Jagielonian University in Kraków was founded in 1791 and as early as in the following year the founder and first director, Professor J. Śniadecki, personally started regular, 3 times a day observations of thermometer and barometer readings. Regrettably, the developing station had to suspend its activities in 1794 as a result of the very unfavourable political situation in the country and financial situation of the university. In the period 1794–1825, observations were effected irregularly. The register of observations is available for 1803–1804 (some incomplete), for the year 1805 (partly), for 1811–1823 and 1824–1825 (partly) (Trepińska and Kowanetz 1997). Between 1826 and now there has been a continuous series of results for air temperature. Preserved registration of the site and observation times exist; the latter corrected by conversion to true mean values (Trepińska 1971). The certainty of the station's permanent location provides quite a good guarantee that the series is homogeneous. Temperature data for the years 1794–1825 were supplemented using the method of multiple regression and this was recognized as the best method meeting the assumption of the least error when seeking missing values in long measurement series (Ustrnul 1997).

To complement the Kraków series, monthly average air temperatures from the above mentioned stations (in Warsaw, Prague, and Vienna) have been utilized.

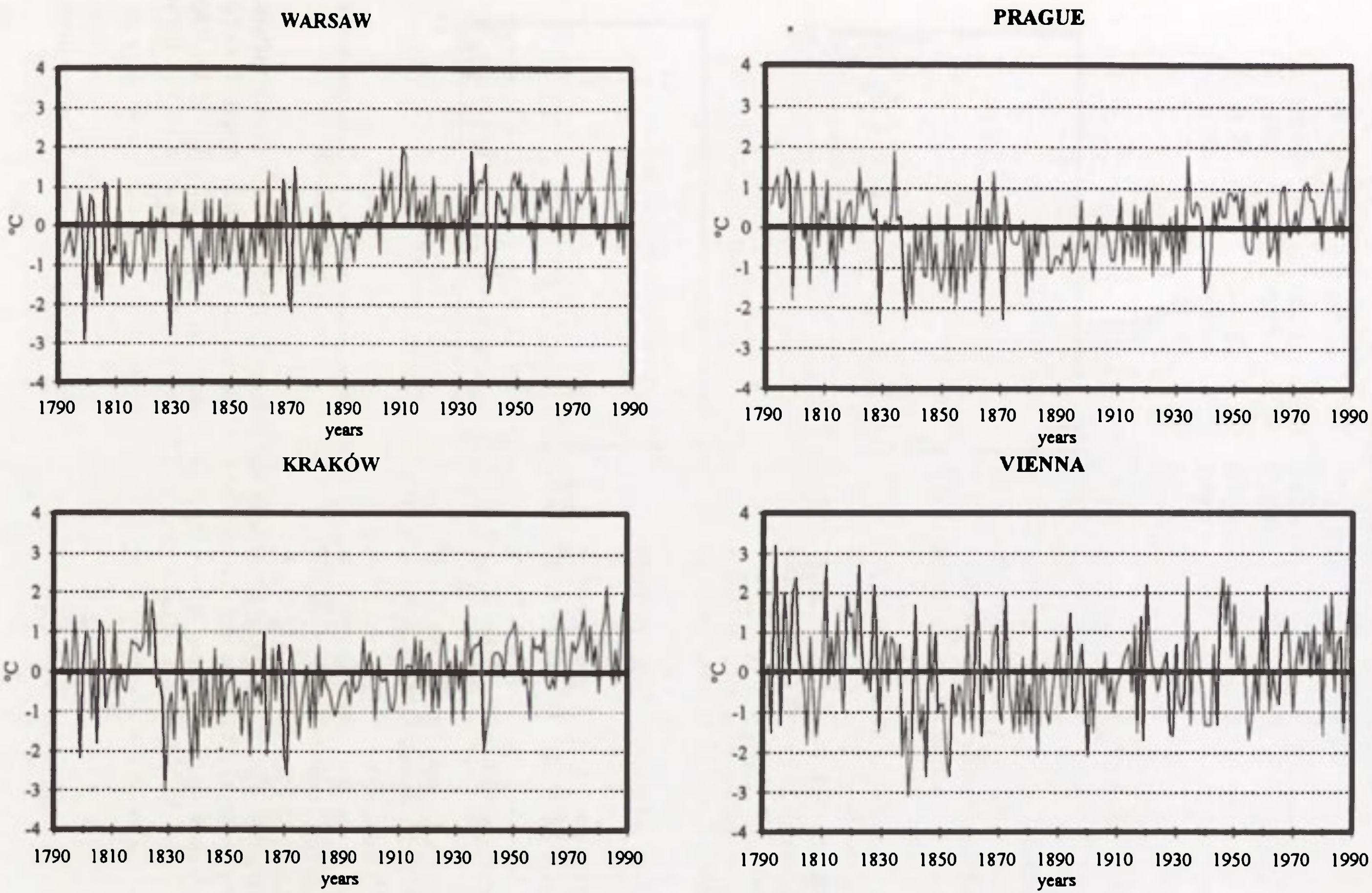


Fig. 4. Deviations from the 200-year mean annual air temperature (1792–1991)

The coordinates of the selected stations are:

	latitude	longitude	altitude
Warsaw	52°13'N	21°02'E	110 m
Kraków	50°04'N	19°58'E	220 m
Prague	50°05'N	14°25'E	202 m
Vienna	48°15'N	16°22'E	202 m

AIMS AND METHODS

The main aim of this synthetic study is to present similarities and differences in the courses of average air temperature according to source data from the oldest meteorological stations in Central Europe. Analyzed was the course of the average annual air temperature and values for the selected months of: January, April, July and October. All the stations have continued to the present in recording air temperature and it therefore seems reasonable to produce this kind of syntheses on the basis of series that are being complemented all the time. Every new study brings some new aspects to the case, particularly if work relates to observed trends and cyclicity. Using a wide range of methods allows for the confirmation or altering of previously uncovered relationships. Among the goals of this study is an attempt at a new approach to the issue of cyclicity in air temperature.

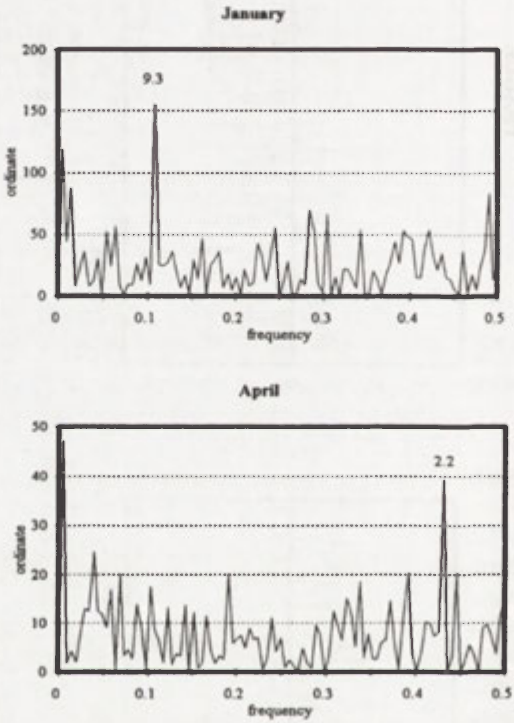
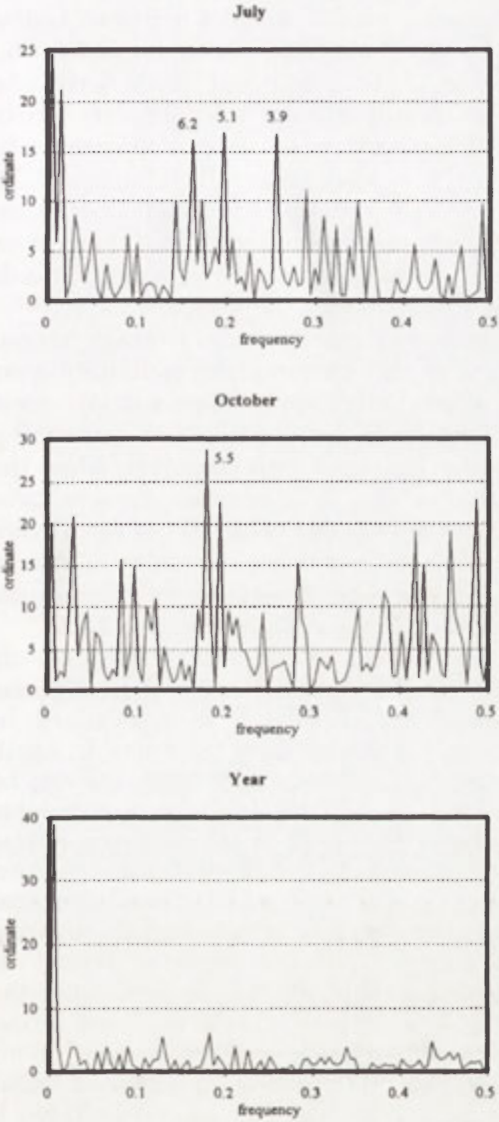


Fig. 5. Periodograms of the mean air temperatures in Kraków (1792–1995)

The methods used in this study are known in statistics. Applied were: the equalization of long series by way of moving means, smoothing by way of a Gauss filter and periodograms. The results are presented in the form of diagrams and tables.



RESULTS

Fig. 1 presents the courses of average annual air temperatures during the examined period after smoothing the data using a Gauss filter. It is striking how great the concordance of the courses for all stations is. The closest values can be seen in relation to the following pairs of stations: Prague–Vienna and Kraków–Warsaw. In general, the greatest differences between stations occurred during the initial period until about the year 1830. The said period is at the same time marked by the greatest variability. Later years did not show such great variability in air temperatures. However, the last decade of the 19th century brought a definite increase in air temperature what may be related to the end of a Little Ice Age. A similar increase also occurred later on, from about the year 1960 onwards. This may be attributed to circulation changes and considerable anthropogenic effects.

Fig. 2 illustrates the course of average annual air temperature in Kraków (upper part of the figure), and the course of average annual deviations for this locality as compared with the so-called areal average value, calculated using data from the other series (for Warsaw, Prague and Vienna). It may be noticed that the average annual air temperature in Kraków is lower than the calculated areal average (positive deviation) except for a few years only in the whole series e.g. 1824: –0,9°, 1900: –0,6° and 1958: –0,3°. After 1970, deviations from annual average values are markedly smaller and that may indicate the increased intensity of western circulation.

Interrelationships in the shaping of air temperature over Central Europe are illustrated by the next figure, Fig. 3. The average from the Kraków series and the average areal series were smoothed with a 9-year Gauss filter. The nine years were taken as an appropriate period for indicating temporal variability within periods about 10 years long. Significant variations in air temperature among the series reaching more than 1°C are above visible in the second half of the 19th century up to 1920s. Differences in the course of values for the two analyzed series are minor after the year 1950. Especially noteworthy is the fact that after 1974, average annual air temperatures in Kraków are higher than the average areal (smoothed values!). The explanations for these interesting differences, among them the warming of Kraków, needs further, more detailed analysis. Here we only signal the issue.

For the approximation and comparison of the course of average annual air temperatures at particular stations, deviations from corresponding 200-year average were defined (Fig. 4). Kraków and Warsaw demonstrate great similarities in the course of these average values. Particularly noteworthy in the Warsaw series is the turn of the 19th and 20th centuries, when the sign of deviations clearly changed to the positive. Values for deviations at three stations (Warsaw, Kraków and Prague) are similar, while those for Vienna are much greater. It is clear from Fig. 4 that the thermal variability of Vienna is greater, as confirmed by calculated standard deviations for the annual averages: Warsaw 0.96°C, Kraków 0.95°C, Prague 0.88°C, Vienna 1.21°C.

In order to examine cyclicity in the course of average annual air temperature and average temperature in the chosen months, periodograms were constructed to allow some characteristic features to be determined. In January, there is a distincly marked cycle repeated every 9.3 years. In April, periodicity is less definite though a cycle repeated every 2.2 years can be noted. It was possible to discover several maxima for July showing variable lengths of cycles, and the same was true for October. However the course of annual averages is distincly lacking in signs of periodicity. The distribution in this case may be taken as random. The periodogram of annual averages corroborates the earlier assumptions that care is justified when drawing conclusions about the occurrence of periodicity in the course of annual air temperature. Numerous earlier attempts support the opinion that the discovery of periodicity depends strongly on the length of the analyzed series.

In addition, studies were undertaken of trends in the course of air temperatures across such long series. For this purpose a number of linear regression equations were solved and the results are presented in Table 1. At each of the examined stations trends in air temperature for January and annual trends have positive signs. In other words, in the cities under discussion, temperature increased. Small negative values are seen in the trends for July in Vienna and in Prague, but in both Warsaw and Kraków all trends are positive. This marked synchronism allows for the division of the area of Central Europe into a northern part, with obvious increases in the selected months, and southern part in which the upward trends were somewhat weaker. It may be assumed that in Warsaw and Kraków there has been a stronger impact of both changes in circulation within the last 200 years and local factors related to the development of these cities.

TABLE 1. Equations for trends in mean values for air temperature (^{o}C) in Warsaw, Kraków, Prague and Vienna (1792–1995)

Station	Month	Equation	b_s
Warsaw	January	y = –30,02 + 0,0139 x	3,47
	April	y = –7,20 + 0,0078 x	1,91
	July	y = 14,65 + 0,0021 x	1,43
	October	y = –2,42 + 0,0055 x	1,70
	Year	**y = –6,12 + 0,0073 x**	**0,87**
Kraków	January	y = –34,66 + 0,0166 x	3,45
	April	y = 1,6 + 0,0036 x	1,97
	July	y = 18,47 + 0,0002 x	1,36
	October	y = 6,95 + 0,0010 x	1,72
	Year	**y = –1,71 + 0,0053 x**	**0,92**
Prague	January	y = –18,31 + 0,0092 x	3,04
	April	y = 11,83 – 0,0014 x	2,21
	July	y = 22,03 – 0,0013 x	1,46
	October	y = 9,93 – 0,00012 x	1,73
	Year	**y = 8,73 + 0,00035 x**	**0,87**
Vienna	January	y = –16,02 + 0,0077 x	2,9
	April	y = 11,38 – 0,0008 x	1,81
	July	y = 23,35 – 0,0020 x	1,39
	October	y = 8,99 + 0,0004 x	1,59
	Year	**y = 7,57 + 0,0011 x**	**1,21**

Explanation: y = a + bx — regression equation, where: x — year, y — mean value for air temperature, b — regression coefficient, b_s — standard error of the estimation

CONCLUSIONS

The use of the longest-existing series for air temperature in Central Europe made it possible to note strikingly consistent courses for average air temperature over the area represented by the aforementioned stations. This is evidence of similar circulation conditions over the last 200 years: a period extremely interesting for climatologists and biologists because of the climatic change occurring — the end of a Little Ice Age and the beginning of a dynamic period of contemporary warming. The established natural factors affecting processes of climate formation have been augmented recently by new ones which been generally have termed anthropogenic.

It was decided that the Kraków station well represents the area of Central Europe as climatic changes there were characterized by significant synchronism. This in turn justified the presentation of air temperature variability in Kraków in the years 1792–1995 as typical for a large area — in the northern, western and southern foothills of the Carpathian Mountains.

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GEOGRAPHIA POLONICA 70, 1997

VARIABILITY OF SELECTED THERMAL CHARACTERISTICS OF THE AIR IN THE CARPATHIAN FOOTHILLS IN THE YEARS 1951–1995

DANUTA LIMANÓWKA
Institute of Meteorology and Water Management
ul. Piotra Borowego 14, 30-215 Kraków, Poland

ABSTRACT: The paper presents an analysis of thermal conditions in the Carpathian Foothills. Examples illustrating the influence of atmospheric circulation on the distribution and multi-year course of air temperature at sites located at the same parallel of latitude are given. This influence relates to the thermal conditions close to the Earth's surface in a given area and to the circulation processes occurring in the upper part of the troposphere. It has been observed that the effects of the circulation of a given type, represented by the index of the Atlantic progression (P), show up in the multi-year course of temperature and differ in character in particular seasons of the year.

KEY WORDS: atmospheric circulation, circulation indices, climatic variability, mean maximum, mean minimum.

INTRODUCTION

The paper aims at a cognition of the fundamental characteristics of atmospheric circulation in southern Poland and their influence on air temperatures.

Besides radiation factors, atmospheric circulation plays a key role in the Carpathian climate. In the consequence, knowledge of the variability of circulation forms in time helps to explain the genesis of changes in particular elements of climate over a given area. Recently, numerous papers have been published describing the relationship between macroscale indices of circulation over Europe and the Atlantic and air temperature (Niedźwiedź 1993; Kłysik 1994; Kożuchowski, Marciniak 1988; Kożuchowski, Trepińska 1990; Kożuchowski 1993). Examination of present-day climatic changes is becoming an important issue and the opinions of climatologists on this question have been presented in the works of H. Raino (1994) and R. Brázdil and Dobrovolný (1993), and in the work entitled "Climate of Europe" (1995). The most recent outcomes of the discussion referring to the changes in extreme temperatures with a simultaneous indication of trend lines for Central and South-Eastern Europe have been presented by R. Brazdil et al. (1996). It might also be interesting to examine variability in circulation over smaller regions and such tasks have been undertaken by E. Cebulak at al. (1995), T. Niedźwiedź (1993), R. Brazdil and P. Dobrovolny (1993) and T. Niedźwiedź (1994).

Characteristics of variability in atmospheric circulation can be presented with a certain approximation through analysis of the frequency of particular synoptic situations. For the purpose of this paper a simple index P, worked out by Murray and Lewis (1966) and based on the circulation catalogue of Lamb (1972) used in Great Britain and modified by Niedźwiedź (1993), has been adopted. The progression index — P (an index of zonal westerly circulation) was calculated by summation of the scores (points) for days with different air flow as follows: W +2, E –2, NW, SW +1, NE, SE –1, N, S = 0.

It is easy to see that high positive values for this index occur with a distinct predominance of air advection from the West, while negative ones point to a blocking of Atlantic Ocean influences and a great frequency of easterly air flow (continental influences).

The present paper contains an analysis of the thermal conditions existing in the Carpathian Foothills in 1951–1995. Particular attention has been paid to showing the influence of continentality and oceanity on trends in the course of air temperature in various parts of the Foothills. The stations Aleksandrowice, Lesko and Ptaszkowa represent the low part of the warm climatic zone in the Carpathians (Hess 1965) and are located at almost the same parallel of latitude. This allows the influence of continentality and oceanity to be examined. The geographical co-ordinates and elevations a.s.l. of these stations are:

Aleksandrowice	49°48'N	19°00'E	398 m above sea level
Lesko	49°28'N	22°20'E	386 m above sea level
Ptaszkowa	49°36'N	20°53'E	520 m above sea level

The first two stations represent concave landforms while Ptaszkowa represents a convex landform.

Variability in mean temperatures in relation to monthly, maximum and minimum values was studied for a year and for seasons defined in the standard way: winter (December–February), spring (March–May), summer (June–August) and autumn (September–November). In the analysis of variability, short-term fluctuations have been eliminated by smoothing, using the method of 5-year moving averages. The analogous criterion has been used in the case of the circulation index P, which is depicted in each figure.

VARIABILITY OF CIRCULATION INDEX P

In the studied 45-year period, the value of the western circulation index P is high if compared to the mean value, being equal to 106.

In the years 1968–1976, the inflow of air masses from the Atlantic was weakened. However, the present period is characterised by a large inflow of air from the west with a maximum in 1990 (245). Negative values, i.e. zonal circulation but with an eastern component, were observed twice in the studied period, in 1963 and 1972. The minimum was recorded in 1963 (–41).

Nevertheless, in particular seasons the index varied significantly. The largest number of negative values was recorded in spring (19) and summer (10) while there were only 1 to 3 cases in the remaining seasons.

MEAN ANNUAL AIR TEMPERATURE

The mean annual temperature of air in the Carpathian Foothills fell in the years 1968–1987. The observed rise in temperature from 1988 was related to the increased frequency of air advection from the Atlantic Ocean (Fig. 1a–c). The trend line in the eastern part of the Carpathian Foothills (Lesko) shows a slight decrease while in the remaining part of the region upward trends were recorded.

Atmospheric circulation most strongly affects the mean annual amplitude of air temperature that is accepted as the simplest measure of climate continentality. It is determined as the difference between the mean temperature of the warmest and coldest months in a year and was accepted as an indicator of continentality by E. Romer (1947). Reduction of annual oscillations in air temperature in the mountains was called "super-oceanity of mountains" by E. Romer.

The values for the amplitude described above become lower if air masses come from the west, and higher if there is air advection from the east. When considering the multi-year course of the annual air temperature amplitudes in the Carpathian Foothills two periods can be distinguished: 1951–1970 — the period of increased influence of continentality and after 1970 — the period of Atlantic influences. The number of years with the most pronounced features of continentality, with annual amplitude greater than 22°C, changed from 7 to 9 cases from east to west.

In particular seasons the following trends were observed (Figs. 2a–c — 5a–c). In winter (December–February, Figs. 2a–c) the air temperature is influenced most strongly by the index of zonal circulation P and a positive trend occurred. The greater intensity of western circulation occurred in the mid-1950s and in the last decade, when the value of the P index reached 119 in 1989, i.e. the highest value in the whole discussed period.

In the period 1951–1995, winter 1989/1990 was the warmest (Aleksandrowice 2.9°C, Ptaszkowa 1.4°C, Lesko 1.2°C). The coolest were the winters of 1962/1963 (Aleksandrowice –7.7°C, Ptaszkowa –7.9°C, Lesko –7.4°C) and 1984/1985 (Aleksandrowice –5.2°C, Ptaszkowa –6.4°C, Lesko –6.7°C).

Negative values for the P index were very often recorded in spring (March — May, Figs. 3a–c) which provides evidence for an intensified zonal circulation with an eastern component. In this season, very high year-to-year variability in the coefficient is characteristic. Thus the warm spring of 1986

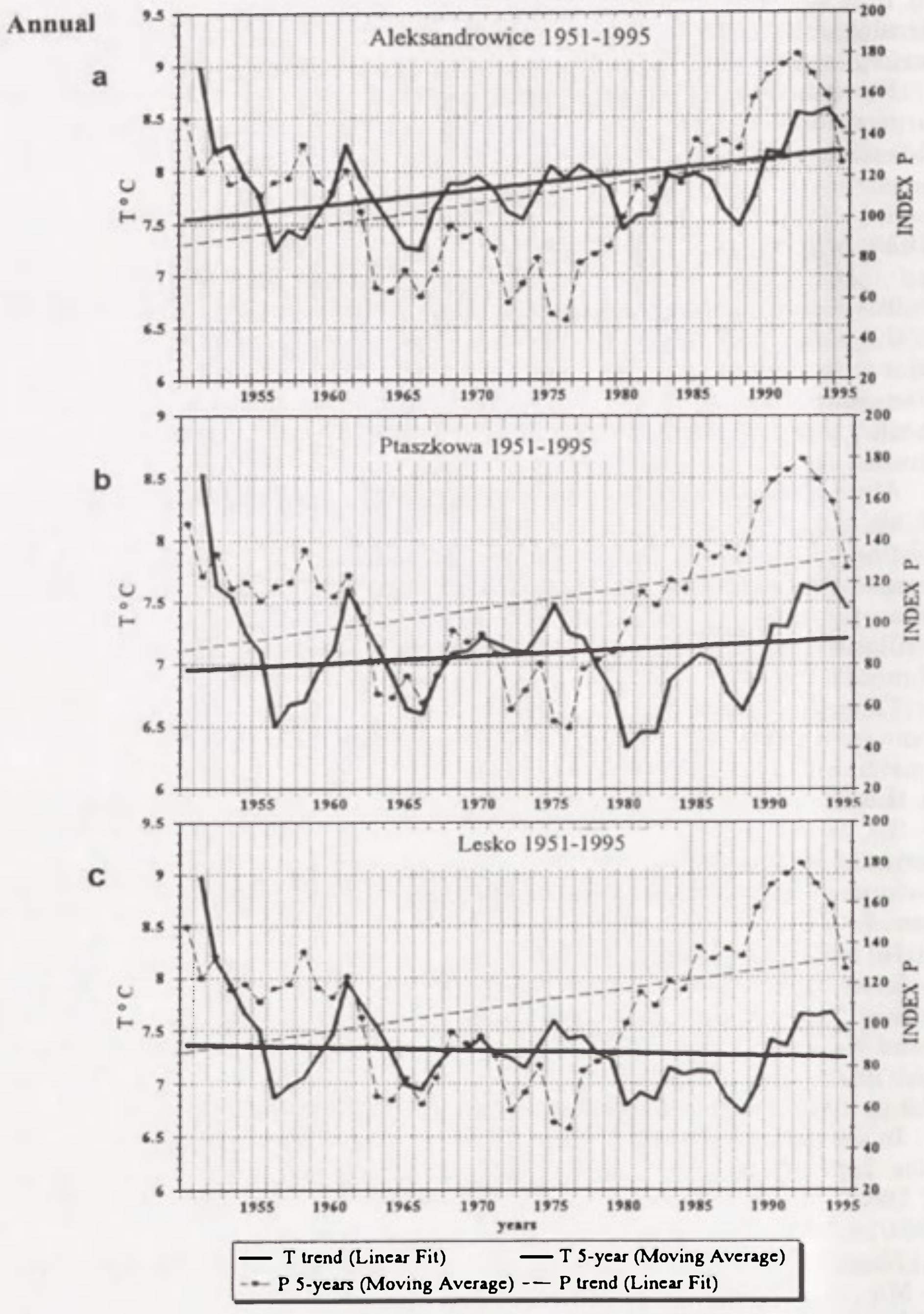

Fig. 1. Annual mean air temperature (T) and progression index (P)

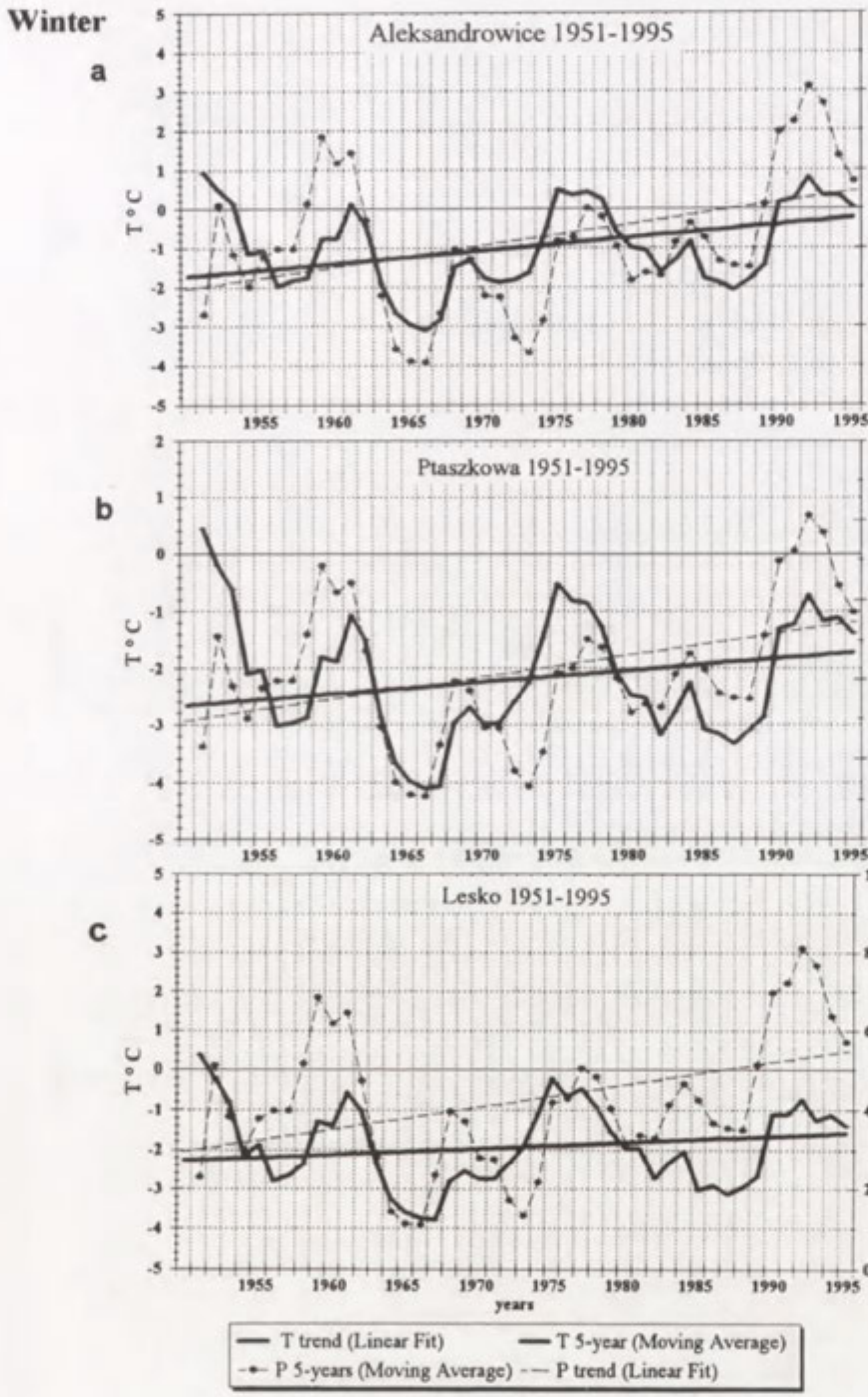

Fig. 2. Mean winter air temperature (T) and progression index (P)

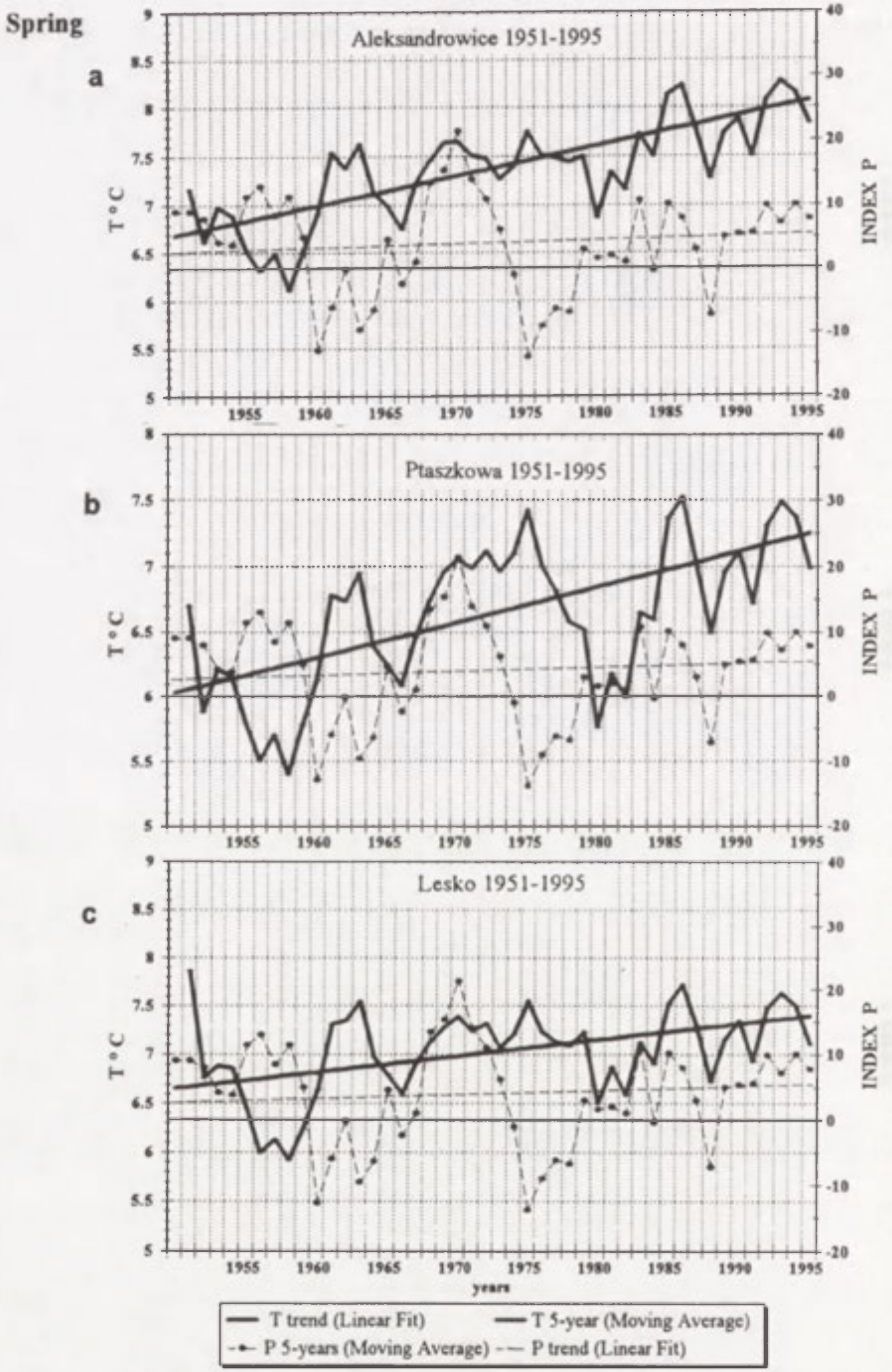

Fig. 3. Mean spring air temperature (T) and progression index (P)

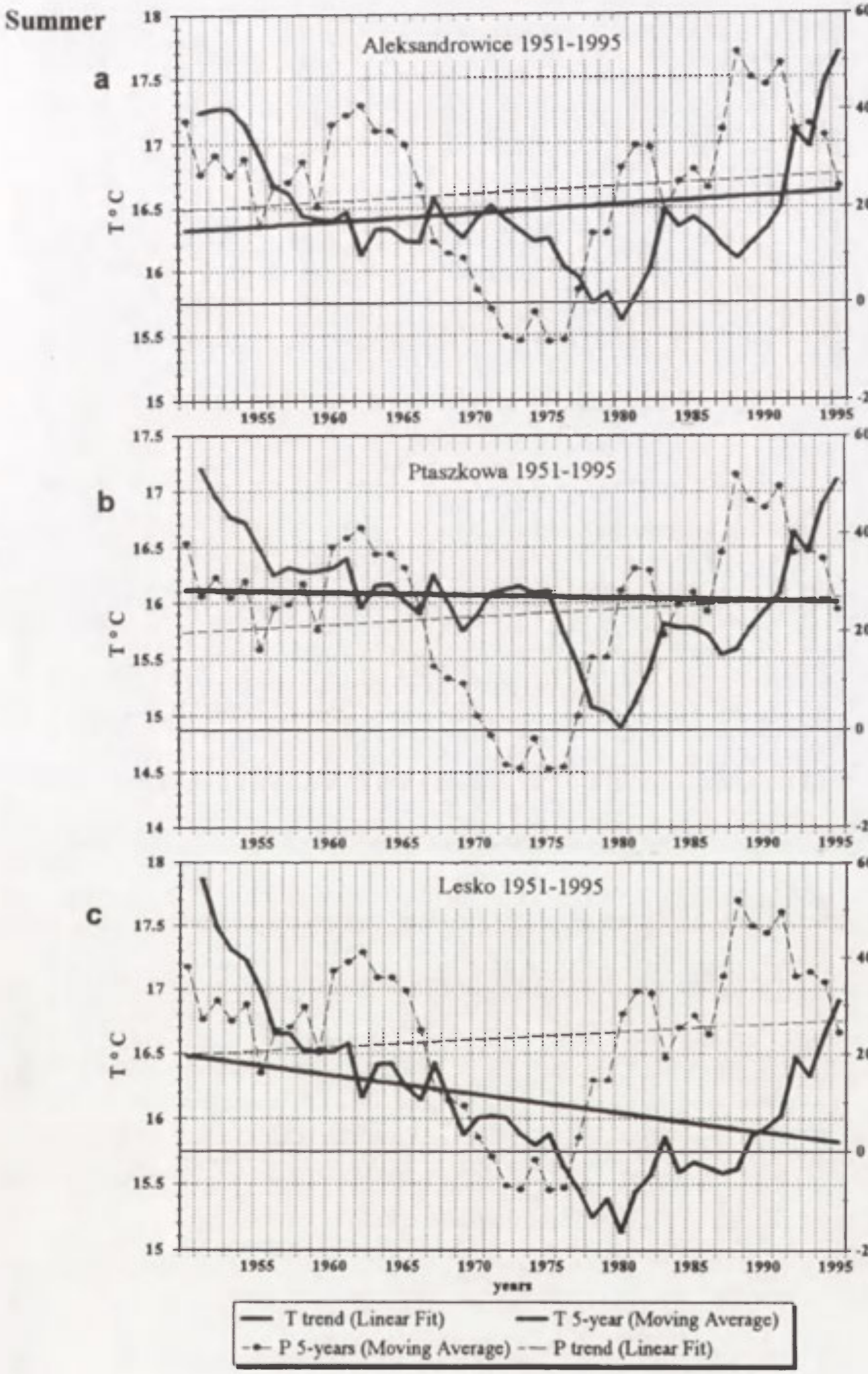

Fig. 4. Mean summer air temperature (T) and progression index (P)

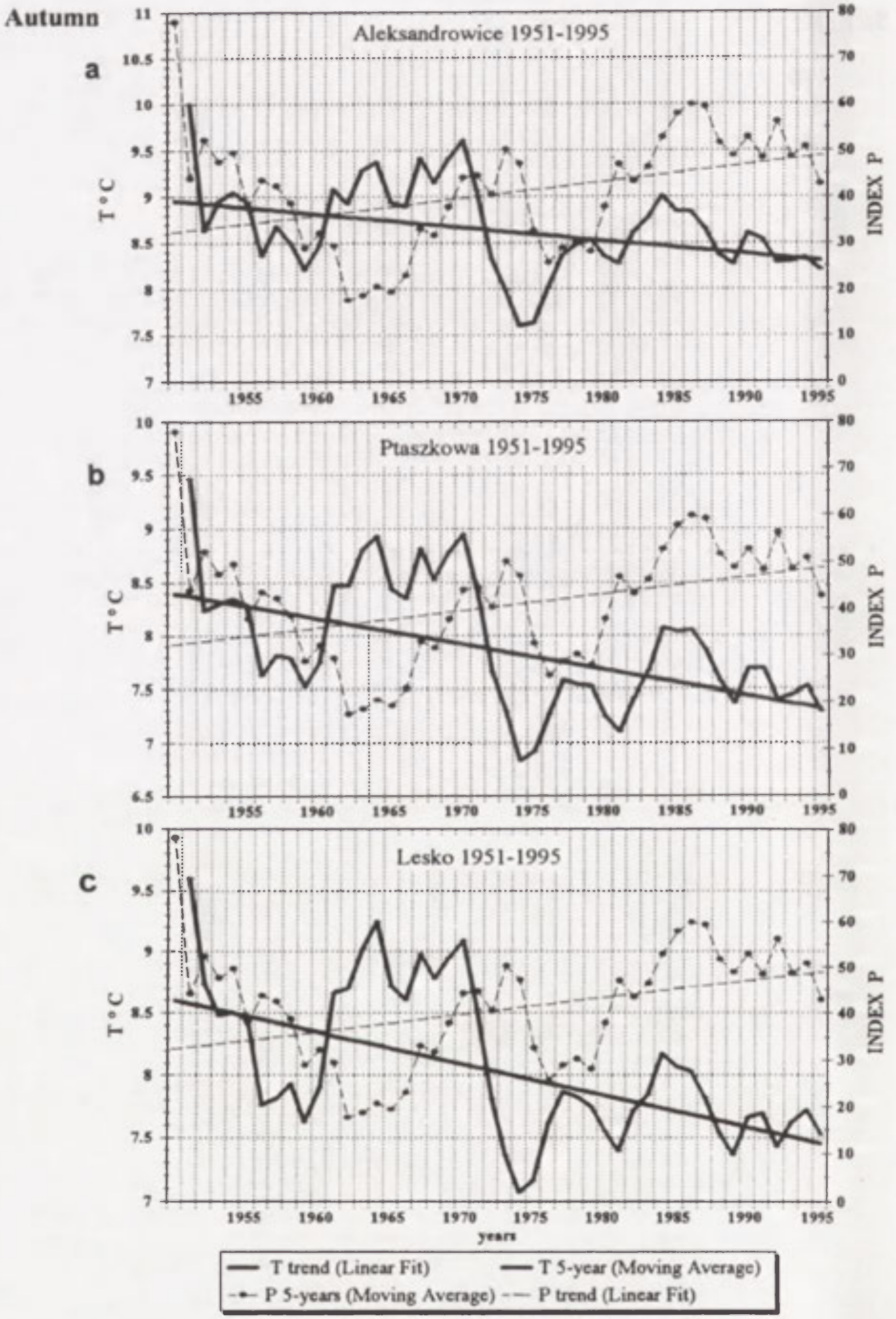

Fig. 5. Mean autumn air temperature (T) and progression index (P)

(Aleksandrowice 8.9°C, Ptaszkowa 8.2°C, Lesko 8.5°C) was followed by the chilliest spring period of 1987 when the mean temperature was only 5.0°C in Aleksandrowice (Ptaszkowa 4.0°C, Lesko 4.4°C). A trend line in Aleksandrowice and Ptaszkowa indicates a definite increase in this season.

In summer (June–August, Figs. 4a–c), the course of the P index is very steady and its values are positive. The summer of 1978 was the warmest until 1992. The lowest summer air temperatures occurred after 1978. In this season, intensification of zonal circulation with an eastern component (negative values of the index) was recorded only in 1971–1975. Trend lines for mean summer air temperatures have opposite directions. In the east (Lesko) there was a significant decrease in air temperature. This was also the case for the middle part of the Carpathian Foothills and was expressed in a smaller gradient for the trend line. In the west a slight increase was noted.

In autumn (September–November, Figs. 5a–c), the zonal circulation with a western component usually prevails. However, year-to-year fluctuations are much larger than in summer. High autumn temperatures were recorded in 1961, 1967 and 1982. The autumns of 1972 (Aleksandrowice 6.9°C, Ptaszkowa 6.4°C) and 1988 (Lesko 5.9°C) were the coolest. At all the stations there was a declining trend in autumn air temperatures while the circulation index P showed an increase in general.

EXTREME AIR TEMPERATURE

The difference between the mean autumn (September–November) and spring (March–May) temperatures can be accepted as a simple measure of oceanity. That has been confirmed in the course of average extreme temperatures in these two seasons (Figs. 6a–d – 7a–d). The curves of the five-year moving averages of extreme temperatures and their trends had opposite signs in the eastern and western parts of the Foothills.

In spring (March–May), despite a large number of negative values for the P index (generally low values) there is an upward trend in both minimum and maximum temperatures (Figs. 6a, c, 7a, c).

In autumn (September–November), a decline in the trend in extreme temperatures is observed, yet the values of the P index increase (Figs. 6b, d, 7b, d).

CONCLUSION

In the Carpathian Foothills there is the strongest relation between air temperature in winter and the discussed index of western zonal circulation P. The curves for winter temperature variability in Aleksandrowice, Ptaszkowa and Lesko are very similar to the pattern of the circulation index P. In the annual course, the largest contrasts in circulation, and hence in air temperature, are between winter — when the western zonal circulation is

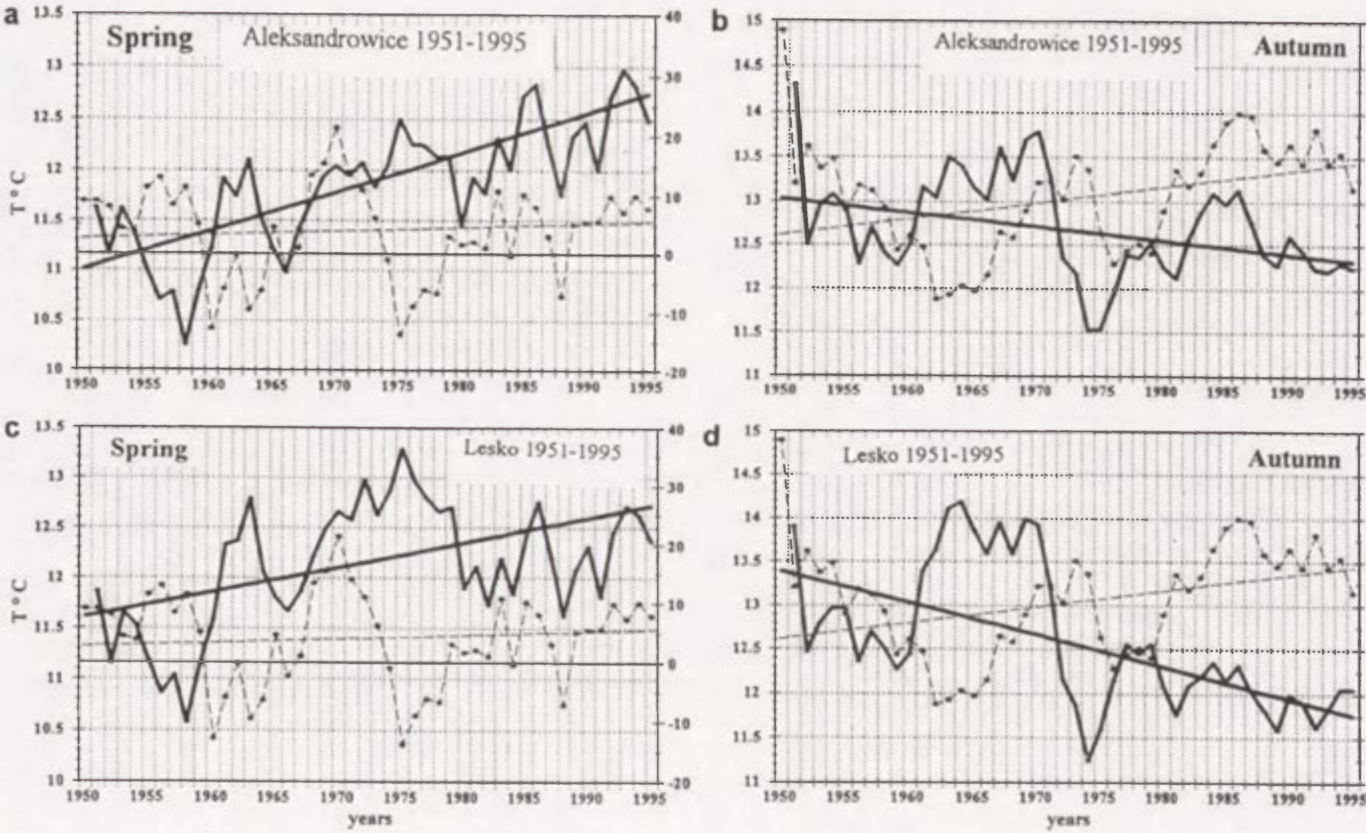

Fig. 6. Mean spring and autumn maximum air temperature (T) and progression index (P)

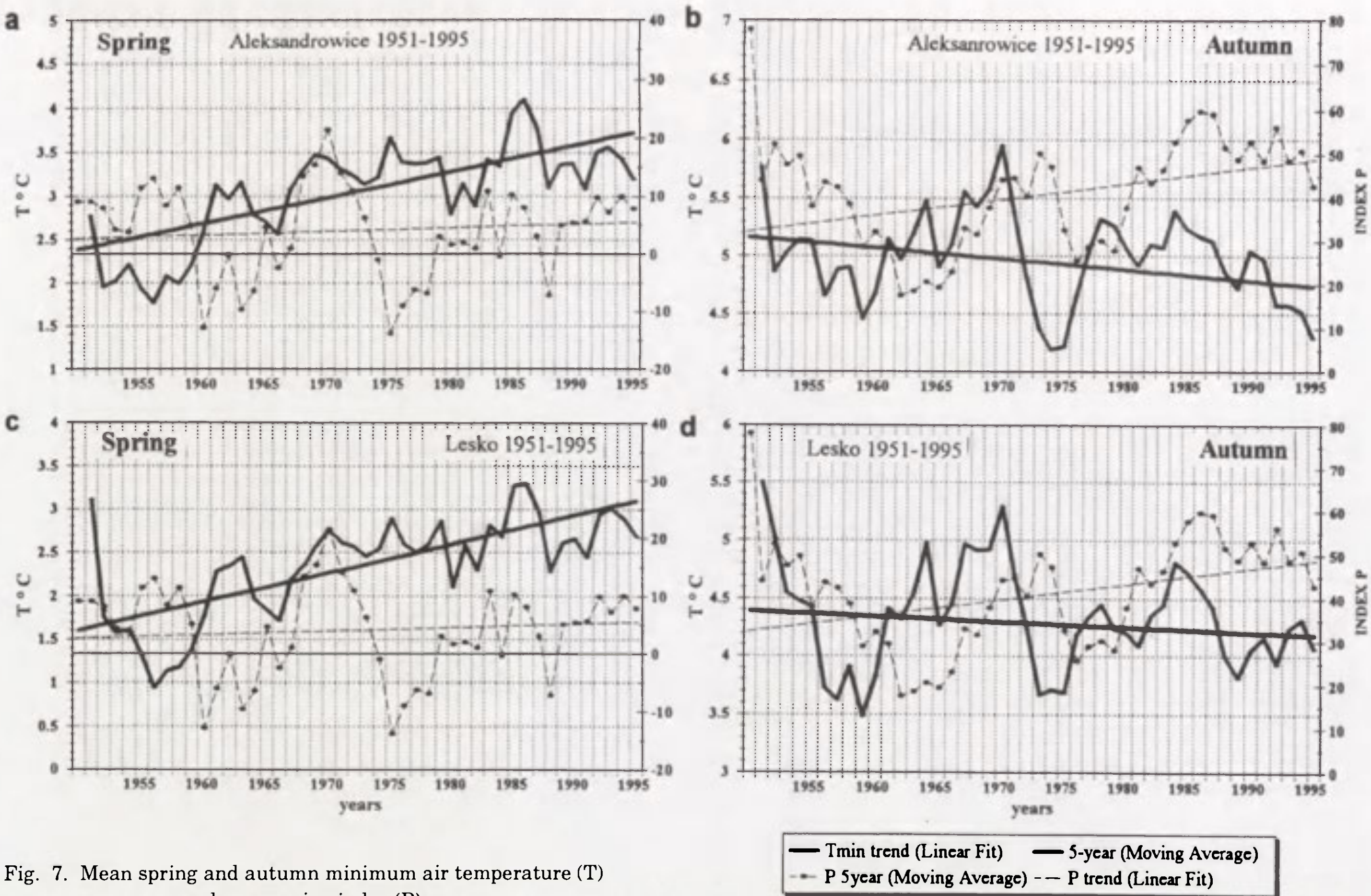

Fig. 7. Mean spring and autumn minimum air temperature (T) and progression index (P)

the most intensive, and spring — when it is weakest. The method of the presented analysis allows for the determination of the fundamental characteristics of the Carpathian Foothills climate resulting from natural variability that usually depends on atmospheric circulation. Moreover, the regularities detected in the distribution of the values and the signs for the trends in southern Poland should be considered when reconstructing air thermal conditions on the regional scale of Central Europe.

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GEOGRAPHIA POLONICA 70, 1997

VARIABILITY OF PRECIPITATION IN SELECTED REGIONS OF THE CARPATHIANS IN THE YEARS 1951–1995

ELŻBIETA CEBULAK

Institute of Meteorology and Water Management
ul. Piotra Borowego 14, 30-215 Kraków, Poland

ABSTRACT: The paper presents an analysis of recent trends for precipitation in the Carpathians on the basis of data for the period 1951–1995. Temporal variability in precipitation was examined based on area-averaged data for the Carpathians and then separately for the eastern and western parts. Overall precipitation totals in the Carpathians show downward trends, which are visible in summer and winter but which contrast with opposite trends in spring and summer. The largest declines in precipitation totals are observed in summer, a phenomenon especially well-pronounced in the western part of the Carpathians, while smaller declines have occured in winter, mainly in the eastern part of the Carpathians. Spring and autumn precipitation in the Carpathians is increasing, but there is agreement between the trend and the course of precipitation in the whole Carpathians. Agreement between the course and trend in precipitation and the cyclonicity index (C) is also observed.

KEY WORDS: Carpathians, areal precipitation, trend, cyclonicity index.

INTRODUCTION

Studies on variability in precipitation in Europe show that precipitation is decreasing in Central and Southern (*Climate of Europe* 1995), as compared with Northern Europe, where an increase is observed, as for example in Scotland (Smith 1995; Jones *et al.* 1994) or Finland (Heino 1994). This paper deals with the variability in precipitation in the Carpathians in a recent 45-year period. Literature on present trends in the precipitation pattern in Poland either disregards mountain areas (DNMI-Raport 1996) or overgeneralises the issue (Kaczorowska 1962; Kożuchowski 1985). Detailed studies referring to recent years, which are believed to be specific, have still been lacking while studies referring to precipitation series after 1990 are only available for selected regions of the Carpathians (Obrębska-Starkel *et al.* 1995).

STUDY METHODS AND MATERIALS

The paper is based on a 45-year precipitation series from 25 stations in the Carpathians for the years 1951–1995, averaged for the whole Carpathian region and separately for the Eastern and Western Carpathians stations (10 and 15 stations respectively) as numerous works on precipitation characteristics in the Carpathians point to the separateness of these regions with respect to trends for and differentiation in precipitation (Schmuck 1965; Lesko 1971; Obrębska-Starklowa 1977; Dobija 1982; Cebulak 1992). The demarcation line between the Eastern and Western Carpathians follows the Dunajec and Biala rivers (Fig. 1).

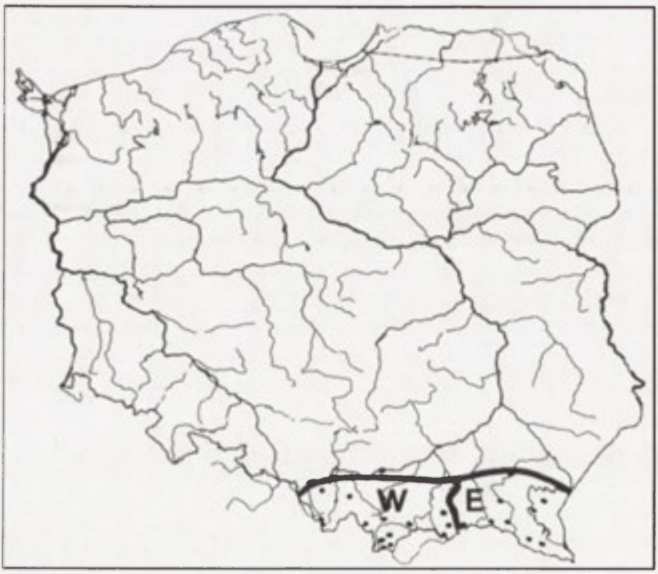

Fig. 1. Division of the Carpathians into two regions (E — Eastern, W — Western) and the locations of the 25 stations

Particular characteristics refer to area-averaged annual and seasonal precipitation. The variability of precipitation was studied based on annual precipitation totals, averaged by 5-year moving averages, and trends for precipitation were determined using trend lines. The data for the stations were averaged disregarding weights for particular stations. Averaging of the data eliminated the influence of local factors and provided an overview of precipitation variability in time.

TRENDS FOR PRECIPITATION IN THE CARPATHIANS

Annual precipitation totals in Kraków show a declining trend. After a distinct maximum in the years 1966–1970 and a smaller one for 1974–1978, precipitation totals have declined steadily. The declining tendency is more clear in the western part of the Carpathians (Fig. 2a) and the trend is less-marked in the eastern part. The courses of precipitation in the light of 5-year moving averages are similar in both parts of the Carpathians. The largest differences in the direction of trends are registered for the years 1953–1963; in the western part of the Carpathians there is a slow increase in annual totals in this period while in the eastern part there is a systematic decrease. Spring precipitation in the Carpathians shows a slight increase. Linear trends are positive (Table 1). When considering areal precipitation in the eastern and western parts, the trends and courses are similar.

TABLE 1. Linear regression equations describing trends for change in annual and seasonal precipitation (y) in the Carpathians in the period 1951–1995 (x–time–year, r–correlation coefficient)

	Year	Spring	Summer	Autumn	Winter
Carpathians	y = –0.87 x + 2556.1 r = 0.098	y = 0.34 x – 426.6 r = 0.098	y = –1.24 x + 2817.1 r = 0.186	y = 0.44 x – 6561.5 r = 0.093	y = –0.19 x + 527.7 r = 0.061
Western Carpathians	y = –1.34 x + 3643.3 r = 0.152	y = 0.06 x + 104.4 r = 0.017	y = –1.68 x + 3724.3 r = 0.227	y = 0.46 x – 709.7 r = 0.105	y = 0.07 x + 25.8 r = 0.022
Eastern Carpathians	y = –0.49 x + 1806.9 r = 0.054	y = 0.72 x – 1235.0 r = 0.201	y = –0.73 x –1755.6 r = 0.114	y = 0.31 x – 427.1 r = 0.062	y = –0.58 x + 1283.7 r = 0.195

In summer, there are the largest declines in precipitation trends (Fig. 2b). When considering the courses of precipitation in summer seasons, averaged for the whole area of the Carpathians, a distinct culmination of precipitation in the years 1968–1974 can be observed. This maximum is particularly well-developed in the western part of the Carpathians and is observed in the years when high precipitation totals triggered severe floods in this area (1970, 1972, 1973). In the course of precipitation in the eastern part of the Carpathians a more pronounced maximum is typical of the 1980s, when floods occurred in the San drainage basin (1980, 1987). Distinct declines in precipitation occur in the 1990s. A downward trend in precipitation in this period resulted from two summer droughts — in 1992 and in 1994. Autumn precipitation shows a slight upward trend where areal precipitation for the whole Carpathians is concerned. If the Carpathians are divided into the eastern and western parts, an agreement in the direction of the trends is observed (Table 1). In general, winter precipitation totals are declining steadily. However, the directions for the trends in each part of the Carpathians are different. In the western part, winter precipitation shows a slight upward trend while in the eastern part there is a distinct decrease (Fig. 2c).

In the recent 45-year period, the changes in precipitation trends expressed using equations have not attained statistical significance but are indicators of contemporary changes in precipitation conditions.

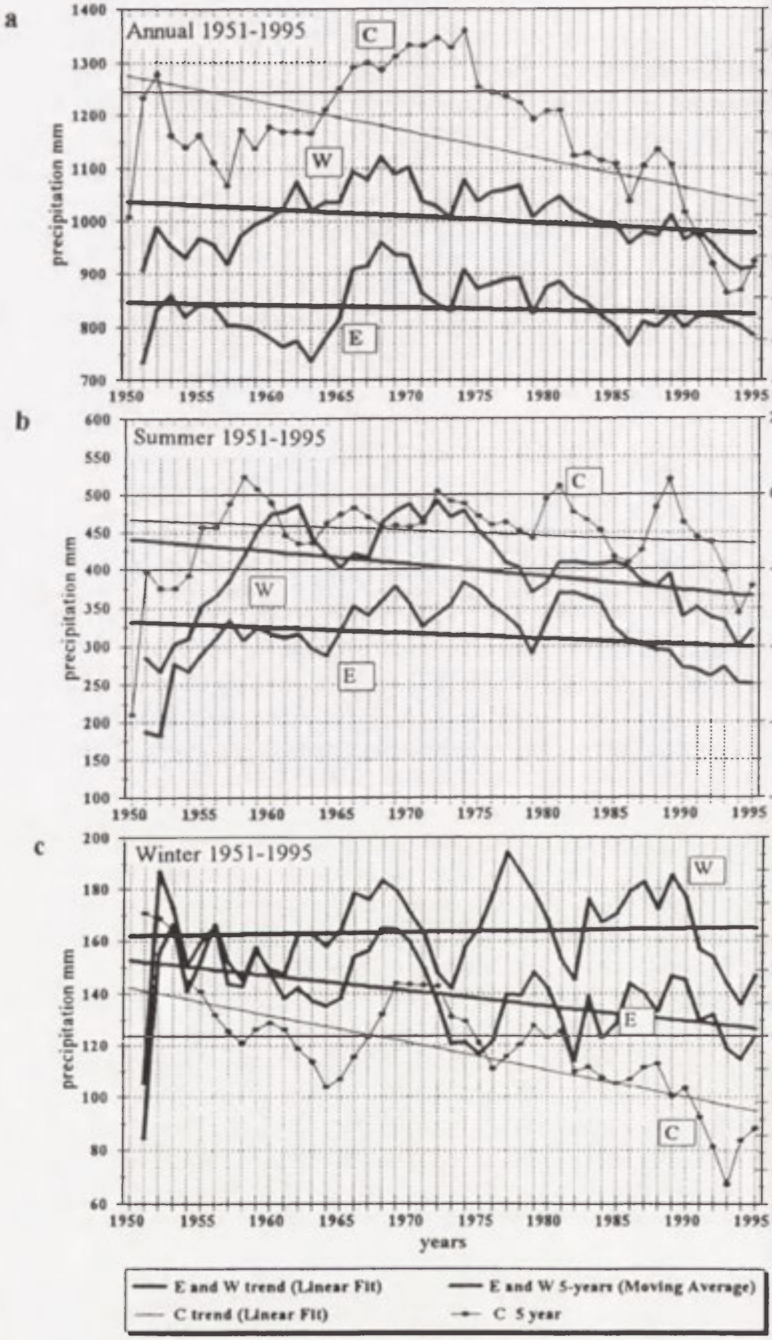

Fig. 2. Precipitation totals and the cyclonicity index C in the eastern (E) and western (W) parts of the Carpathians for: a — whole year, b — summer, c — winter

DEVIATIONS OF PRECIPITATION TOTALS FROM MULTI-YEAR MEANS

The courses of multi-year precipitation series have been compared with mean values for the whole period of 1951–1995 that have been accepted as a "norm". Deviations of the annual and seasonal totals from the multi-year averages have been calculated. A division into dry and wet years has been adopted after Kaczorowska (1962) and intervals in this division are marked in the figures.

Deviations of the annual precipitation totals from the multi-year mean differ in the two parts of the Carpathians and fall onto different years (Figs 3a, 4a). The largest deviations from the multi-annual mean in the whole Carpathians are recorded in 1974. The more pronounced maximum in that year was noted in the eastern part, where precipitation was greater by 40 per cent than in the average year. In the western part of the Carpathians, 1970 stood out with precipitation higher by 23 per cent than in an average year (one of the largest floods in the Carpathians). The driest year in the Western Carpathians, 1993, provided only 80 per cent of the "norm", but in the east this year was not an exceptional one. From 1990 to 1995, annual precipitation totals in the subsequent years are lower than the multi-year mean and this is more clear in the western part of the Carpathians. In spring, the largest deficit in precipitation was recorded in 1982 (Table 2). Then rainfall was lower by 34 per cent than in an average spring in the Carpathians. The wettest spring of 1989 provided precipitation higher by 52 per cent than in a normal spring.

TABLE 2. Annual and seasonal precipitation statistics 1951–1995

	Year	Spring	Summer	Autumn	Winter
		III-V	VI-VII	IX-XI	XII-II
		Mean (mm)			
Carpathians	928	216	367	199	154
Western Carpathians	1006	232	402	207	164
Eastern Carpathians	834	192	315	188	139
		Standard deviation (mm)			
Carpathians	115.8	45.8	88.0	61.0	40.5
Western Carpathians	114.3	46.7	96.4	57.5	42.3
Eastern Carpathians	119.8	46.7	83.3	65.8	38.6
		Coefficient of variation (%)			
Carpathians	12.3	21.2	24.0	30.6	26.3
Western Carpathians	11.4	20.2	24.0	27.8	25.8
Eastern Carpathians	14.4	24.4	26.5	35.0	27.7

From 1986 to 1995 a deficit in precipitation in summer periods is recorded (Figs 3b, 4b). The summer periods of 1989 and 1991 were exceptional and then precipitation was within the norm. In the driest summer of 1992 (drought in Poland) precipitation 44 per cent lower than the multi-year mean, while the next driest summer, of 1994, had precipitation 33 per cent lower than the norm. In the eastern part of the Carpathians precipitation has been below the norm in all years since 1986. Here, the largest deviation from the multi-year mean, 72 per cent above it, was recorded in the wettest summer of 1980. The wettest autumn of 1952 provided even 92 per cent more precipitation than average. In the eastern part of the Carpathians, the autumn periods of 1952, 1974 and 1992, with precipitation 100 per cent, 91 per cent and 94 per cent above the norm are exceptional. According to Kaczorowska (1962), all the autumn periods mentioned above were extremely wet (Table 2). When considering the course of winter precipitation in the Carpathians, the periods above the norm are in the years 1964/1965–1967/1968. In the western part, the subsequent wet winter periods occurred in 1973/1974–1976/1977 and 1985/1986–1988/1989 (Figs 3c, 4c). When considering the multi-year course in the eastern part, winter precipitation lower than the norm has been predominant from 1971/1972. This pattern was interrupted only by a few winter seasons when precipitation was higher than average.

PRECIPITATION TOTALS IN THE YEARS 1951–1995

The mean annual precipitation total for the 45-year period was 938 mm for the whole Carpathians, the standard deviation was 115.8 mm and the variability coefficient 12.3 per cent. In the eastern and western parts of the Carpathians, precipitation and corresponding statistical characteristics differ significantly (Table 2). The mean annual precipitation total in the western part of the Carpathians exceeded 1000 mm while in the eastern part it reached 850 mm. As a rule, precipitation is much greater in the western part than in the eastern part. Extreme values for the wettest and driest months, seasons and years differ in the Eastern and Western Carpathians. Moreover, differences relate also to the years when these extreme values were recorded. Table 3 shows the extreme values for precipitation (five wettest and driest cases) for months, seasons and years.

RELATION BETWEEN PRECIPITATION AND ATMOSPHERIC CIRCULATION

The trends in precipitation in the Carpathians are confirmed by studies on atmospheric circulation. The variability of the cyclonicity index — C (Niedźwiedź 1993) that denotes under which pressure systems weather was developed in a given period, was analysed in relation to the course of precipitation in particular seasons and in a year in the whole discussed

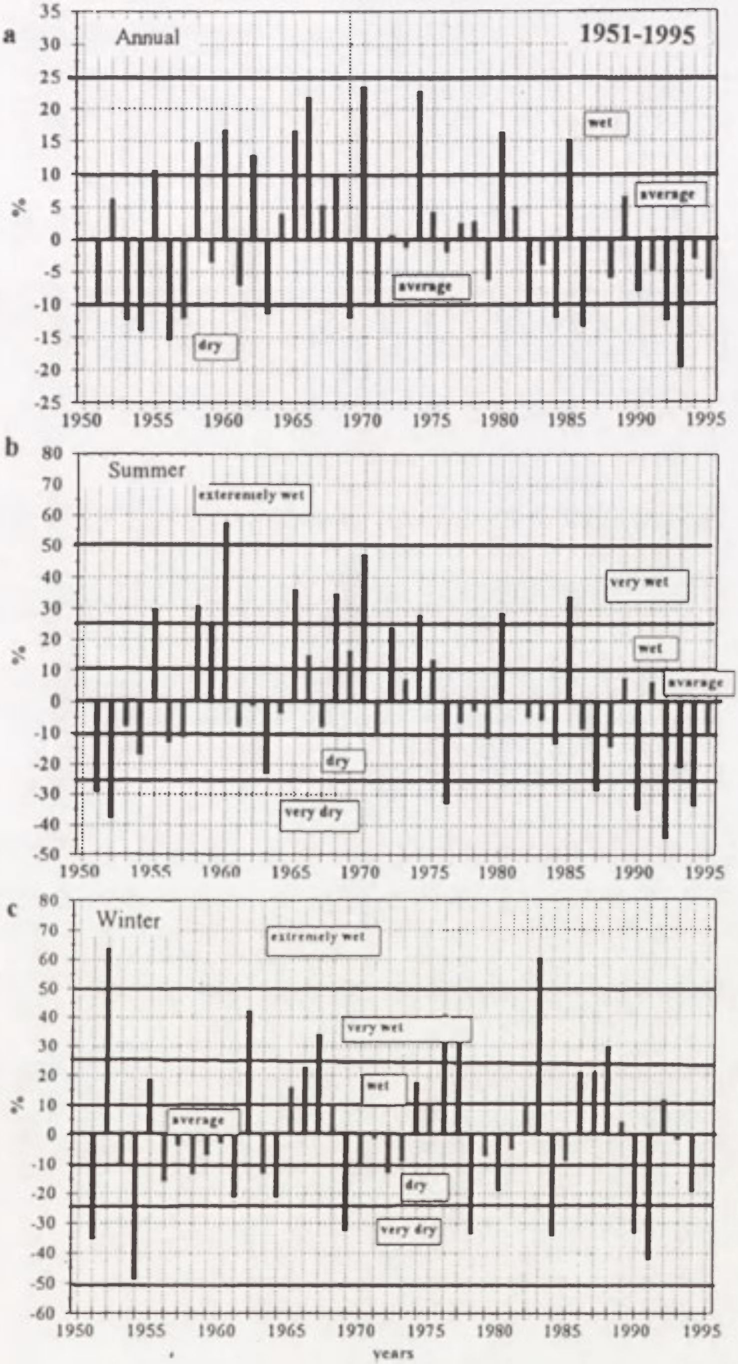

Fig. 3. Percentage deviations of precipitation totals from the multi-year means for: a — whole year, b — summer, c — winter, in the Western Carpathians

TABLE 3. 1951–1995 precipitation extremes by month, season and calendar year

Region	Rank	Month	mm	Spring	mm	Summer	mm	Autumn	mm	Winter	mm	Year	mm
						Wettest							
Carpathians	1	July 1980	273	1989	328	1980	532	1952	382	1951/52	256	1974	1214
	2	July 1960	249	1966	326	1965	530	1974	328	1982/83	251	1966	1179
	3	July 1970	239	1951	301	1960	526	1992	322	1976/77	219	1970	1167
	4	June 1974	223	1994	298	1970	521	1980	317	1961/62	212	1980	1139
	5	August 1972	206	1962	283	1974	513	1964	304	1966/67	207	1965	1117
Western Carpathians	1	July 1980	314	1966	360	1960	634	1952	372	1951/52	268	1970	1241
	2	July 1970	282	1994	333	1970	592	1980	328	1982/83	262	1974	1233
	3	June 1974	252	1951	323	1965	548	1964	312	1961/62	232	1966	1225
	4	August 1985	240	1962	323	1968	542	1974	300	1975/76	230	1960	1174
	5	July 1968	233	1989	318	1985	538	1990	197	1966/76	220	1965	1172
Eastern Carpathians	1	July 1980	294	1989	337	1980	542	1952	376	1951/52	226	1974	1166
	2	October 1974	229	1970	261	1974	504	1992	364	1982/83	219	1966	1093
	3	June 1974	228	1966	266	1965	494	1974	358	1976/77	206	1980	1083
	4	May 1989	199	1966	260	1953	469	1980	293	1954/55	198	1965	1040
	5	June 1973	189	1978	258	1966	436	1964	277	1952/53	189	1970	1022
						Driest							
Carpathians	1	October 1951	3	1982	143	1992	210	1959	85	1953/54	72	1993	765
	2	March 1974	3	1969	158	1952	216	1986	89	1983/84	95	1986	784
	3	February 1976	3	1956	166	1994	132	1982	120	1990/91	96	1954	789
	4	February 1954	9	1974	167	1975	132	1951	125	1977/78	103	1961	797
	5	December 1972	11	1973	167	1990	259	1993	127	1989/90	109	1982	802

Western Carpathians	1	March 1974	7	1969	149	1992	224	1959	93	1953/54	84	1993	807
	2	October 1951	11	1982	169	1952	251	1986	105	1990/91	95	1956	850
	3	February 1976	11	1956	182	1990	262	1951	134	1983/84	107	1954	865
	4	October 1995	11	1974	184	1994	167	1982	137	1977/78	108	1986	872
	5	December 1972	11	1992	188	1976	170	1969	142	1989/90	109	1992	880
Eastern Carpathians	1	February 1976	1	1982	109	1952	177	1986	77	1953/54	65	1961	625
	2	March 1974	2	1959	122	1951	187	1959	81	1983/84	79	1982	657
	3	October 1951	3	1953	124	1976	187	1961	106	1979/80	87	1986	667
	4	October 1962	6	1961	129	1994	188	1982	103	1977/78	93	1959	671
	5	February 1954	8	1981	139	1951	197	1993	109	1972/73	95	1954	701

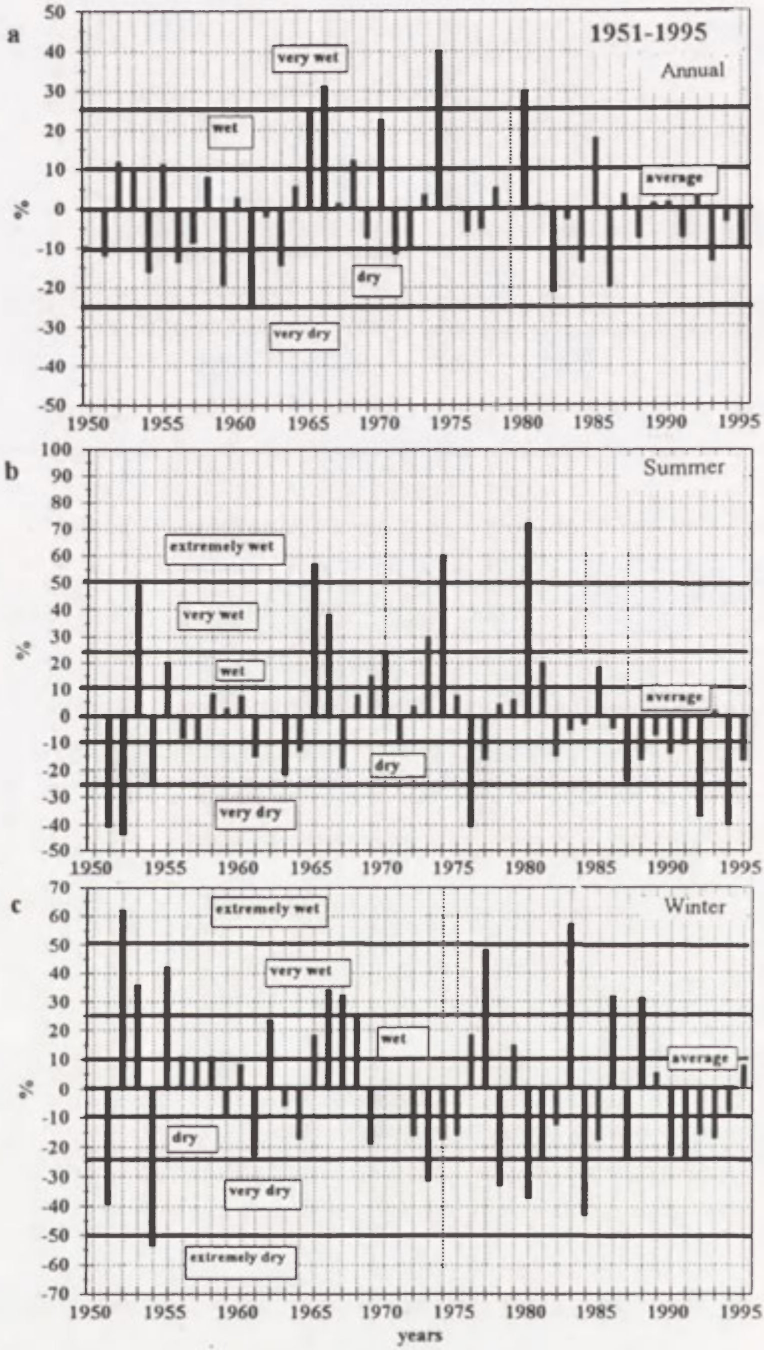

Fig. 4. Percentage deviations of precipitation totals from the multi-year means for: a — whole year, b — summer, c — winter, in the Eastern Carpathians

period 1951–1995. Positive values of the index C indicate the prevailing influence of lows while negative values are recorded if highs occur frequently. There is an agreement between the course and tendency in precipitation and the cyclonicity index C (Fig. 2a–c). Positive values of C were noted in the periods with high precipitation in 1965–1975. After 1975, index C decreases systematically, although a slight increase in the second half of the 1980s coincides with a period of higher annual precipitation. The highest value for this index is in 1974, the wettest year in the 45-year series, and this explains such a wet year. The especially wet autumn of 1952 is also confirmed by a positive value for index C. The cyclonicity index and precipitation are best correlated with annual precipitation totals in the western part of the Carpathians, and where seasons are concerned with the autumn totals in the whole Carpathians and with the winter totals in the eastern part (Table 4).

TABLE 4. Correlation of annual and seasonal precipitation totals with cyclonicity index C for the Carpathians and their Eastern and Western parts in the period 1951–1995

	Year		Spring		Summer		Autumn		Winter	
	a	r	a	r	a	r	a	r	a	r
Carpathians	1.03	0.46	0.76	0.39	1.52	0.32	1.49	0.58	0.55	0.33
Western Carpathians	0.25	0.50	0.71	0.35	1.69	0.33	1.35	0.55	0.36	0.21
Eastern Carpathians	0.88	0.38	0.80	0.40	1.14	0.26	1.57	0.56	0.77	0.49

a — slope of linear regression mm/index, r — correlation coefficient

CONCLUSIONS

Downward trends in annual precipitation totals are being maintained in the whole Carpathians. The declines are twice as large in the western part as in the eastern part. Such trends in precipitation are also observed in seasons — most marked in summer and least in winter. The decrease in summer precipitation totals is twice as great in the western part of the Carpathians as in the eastern part. Precipitation in the Carpathians is increasing in spring and autumn. The largest growth in precipitation is in spring, but the higher values are in the eastern part, and lower ones in autumn in both the regions albeit more significant in the western part of the Carpathians. Trends in contemporary changes in precipitation in the Carpathians are confirmed by the studies on atmospheric circulation and supported by the cyclonicity index C.

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LONG-TERM VARIABILITY IN THE NUMBER OF DAYS WITH PRECIPITATION IN KRAKÓW IN RELATION TO CIRCULATION PATTERNS

ROBERT TWARDOSZ
Department of Climatology, Institute of Geography of the Jagellonian University
ul. Grodzka 64, 31-044 Kraków, Poland

ABSTRACT: The paper analyses long-term variability in the number of days with precipitation in Kraków in relation to changes in atmospheric circulation. Data on annual, semi-annual and seasonal numbers of days with precipitation > 0.1 mm in the 1814–1995 period and data on days with precipitation > 1.0 mm and > 10.0 mm for the years 1850–1995 were used. For precipitation threshold values, averages, maxima, minima, standard deviations and variability coefficients are presented. For the 1874–1995 series, correlation coefficients between the number of days with precipitation and the index of cyclonicity – C, determined on the basis of the classification of circulation types proposed by T. Niedźwiedź, are calculated. It was found that the number of days with precipitation ≥ 0.1 mm and > 1.0 mm shows significant positive trends in the cold half of the year and in the winter period, and negative trends in the warm half of the year and in the summer period. The variation in the number of days with precipitation ≥ 0.1 mm and ≥ 1.0 mm shows significant correlation with fluctuations of the C index which is most pronounced in the cold half of the year.

KEY WORDS: variability, trends, number of days with precipitation, atmospheric circulation, Kraków.

INTRODUCTION AND OBJECTIVE

Kraków is one of the few places in Europe which may boast a 147-year-long record of precipitation measurement, and even more importantly, an uninterrupted record conducted in the same place, which began in August 1849. The operation of a meteorological station in this city dates back to the 18th century. Materials regarding measurements from this station are extremely valuable as it has been regarded as a base station for studies on the fluctuation of climate in Central Europe.

The variability in pluviometric conditions in Kraków has been assessed mainly through analysis of total precipitation (Trepińska 1969, Hess 1974, Kożuchowski and Trepińska 1986). It was emphasised that precipitation shows variability of a cyclical nature and does not present a clear trend (Twardosz 1995). The studies omitted analysis of the time sequence of days with precipitation, paying attention to the spatial distribution in Poland only (Olechnowicz-Bobrowska 1970).

Because the number of days with precipitation shows a close correlation with precipitation totals (Olechnowicz-Bobrowska 1970), it may be assumed that this constitutes an equally good indicator in evaluating pluviometric conditions as would the total precipitation. An additional reason for using the Kraków series of measurements regarding the number of days with precipitation is its extraordinary length. On the basis of preserved log books of daily meteorological observations which recorded precipitation under the appropriate dates, the number of days with precipitation ≥ 0.1 mm was reconstructed from as early as 1814. This also provides a possibility to reconstruct sums of precipitation empirically on the basis of linear regression equations for the years 1814–1849. This paper provides a certain contribution to the reconstruction of the climate in the first half of the 19th century and its results can be extrapolated on to a broader area.

The aim of this study was to determine regular trends in the long-term variability in the number of days with precipitation in Kraków in relation to changes in atmospheric circulation.

SOURCE MATERIALS AND METHODS

In implementing this project use was made of data from the climatological station of the Institute of Geography, Jagellonian University, regarding annual, semi-annual and seasonal numbers of days with precipitation ≥ 0.1 mm for the 1814–1995 period and precipitation ≥ 1.0 mm and ≥ 10.0 mm for 1850–1995. This station is situated in the centre of Kraków, within the premises of the Kraków Botanical Garden (φ = 50°04'N, λ = 19°58'E, h = 220 m a.s.l.).

Conditions of variability in atmospheric circulation were determined using the cyclonicity index — C. It was calculated for classification of the types of circulation for southern Poland for the 1874–1995 period, according to Murray and Lewis's method (Niedźwiedź 1993a, 1993b). The C index is an absolute number expressing the number of points for the analysed period which are allocated to particular types of synoptic situations.

For specific threshold values of the number of days with precipitation, variabilities are presented for average, maximum and minimum values, for standard deviations and variability coefficients. In characterising the long-term variability, 11-year moving averages and regression analysis were used, and statistical significance determined by the Spearman rank correlation coefficient (r_s) (Sneyers 1990).

For the 1874–1995 series and for normal periods, correlation coefficients were determined between the number of days with precipitation and the C index.

THE NUMBER OF DAYS WITH PRECIPITATION >0.1 MM IN THE YEARS 1814–1995

The multiannual average of annual number of days with precipitation ≥ 0.1 mm in Krakow is 171 (Table 1), which constitutes 47 per cent of days in the year. In normal thirty-year periods, the averages changed from 171 days in the period 1931–1960 to 176 days in the period 1901–1930. This indicates that in terms of average values, the number of days with precipitation shows little variability. For this reason, this measure was analysed for the entire 1814–1995 series only, without presentation of respective values for normal periods.

TABLE 1. Statistical parameters of the number of days with precipitation ≥ 0.1 mm in Krakow (1814–1995)

	Mean	Max.	Min.	δ	V (%)
year	171.0	231	106	21.3	12.5
cold half-year	86.0	113	49	12.9	15.0
warm half-year	85.1	128	50	14.6	17.2
spring	42.7	68	21	7.5	17.5
summer	44.1	69	22	8.8	20.0
autumn	41.1	64	19	8.9	21.7
winter	43.2	67	20	8.7	20.2

δ — standard deviation
v — variability coefficient

In an annual period, the number of days with precipitation is equally distributed between cold and warm halves of the year (Table 1). In particular seasons, the averages are similar and vary from 41 days in autumn to 44 days in summer. A record high (231) was recorded in 1844, in which there were as many as 63 per cent of days with precipitation. The lowest number (106) was recorded in 1819, which had precipitation on 29 per cent of days. The range of the number of days with precipitation ≥ 0.1 is thus 125 days. In various seasons both minimum and maximum values are close to one another. The standard deviation values for the number of days with precipitation are greater in the warm half-year period than in the cold one. Among seasons, the least deviation occurs in spring, the most in autumn.

The variability coefficient values show that the number of days with precipitation in all of the periods considered in this study manifests less variability than total precipitation values. The variability in annual precipitation in Kraków is 16 per cent and is regarded as moderate (Kożuchowski and Trepińska 1986). The number of days with precipitation in the warm half-year period shows greater variability (17.2 per cent) than in the cold one (15.0 per cent). Among seasons, the greatest variability occurs in autumn (21.7 per cent), and the lowest in spring (17.5 per cent).

The long-term record of the number of days with precipitation shows fluctuations (Fig. 1) which are reflected in the increases in the lowest values and decreases in the highest ones. Four periods of high values can be indicated: the 1830s and 1840s, the end of the 19th century and the beginning of the 20th century; and also five periods of low values: 1814–1828, the 1850s and 1860s, 1920s, 1940 and 1950s, and the past fifteen years 1981–1995. These periods coincide with years of high and low values for total precipitation. This is signified by a high correlation coefficient between the two (r = 0.610), significant at the 0.05 level.

The variability in the annual number of days with precipitation correlates better with the variability in the number of days in the warm half-year period (r = 0.838) and the autumn (r = 0.713) than in the summer (r = 0.687), spring (r = 0.660) or the cold half-year period (r = 0.649).

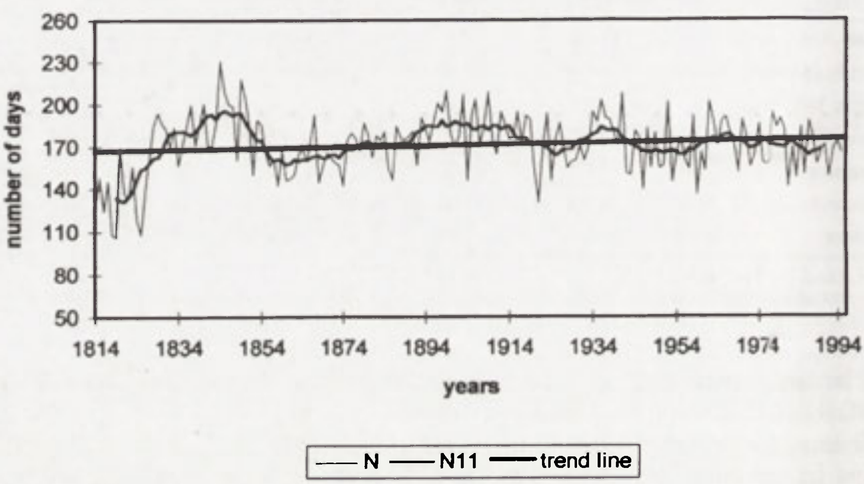

Fig 1. Long-term variability in the annual number of days with precipitation >0.1 mm in Krakow (N — values for each year, N11— 11-year moving averages)

Up to the end of the 1930s, the variability in the number of days with precipitation in the warm and cold half-year periods showed more or less similar trends (Fig. 2). From the 1940s to the year 1995, these trends were in the opposite direction, i.e. for an increase in the number of days with precipitation in the warm half-year period accompanied by a decrease in the cold half-year period. In the whole (1814–1995) series of the annual number of days with precipitation ≥ 0.1, the line representing the trend shows neither increase nor decrease. This is confirmed by a low value for the Spearman rank correlation coefficient (r_s = 0.084), non-significant at the 0.05 level. One may reason that the lack of a trend is caused by the length of the series, because with a lengthened observation period trends tend to disappear. When considering the number of days with precipitation over shorter periods, taking into account natural fluctuations, trends significant at the 0.05 level were found, positive and negative alternating. They occurred in the following years: 1826–1844 (r_s = 0.432), 1845–1874 (r_s = –0.482),

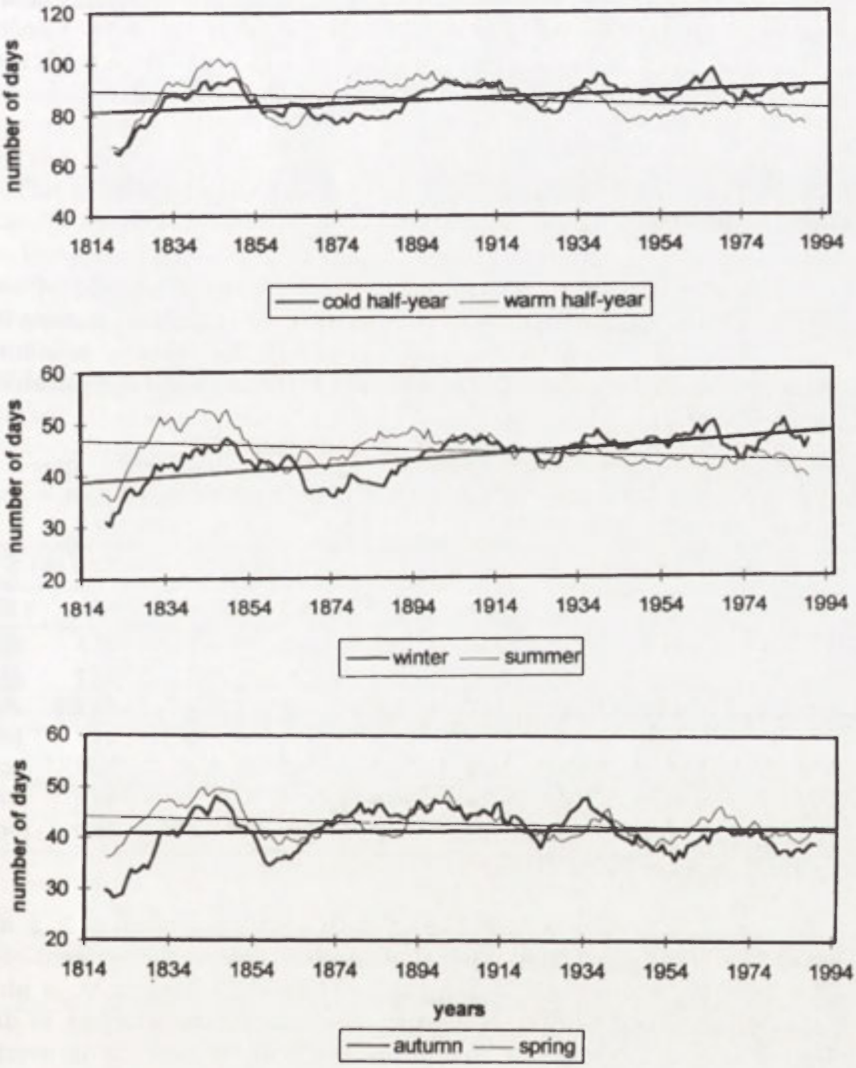

Fig. 2. Long-term course of seasonal 11-year moving averages and trend line for the number of days with precipitation > 0.1 mm in Krakow

1875–1899 (r_s = 0.471) and 1962–1995 (r_s= –0.366). It should be noted that in recent years, beginning in the 1960s, and against the background of a strong downward trend in annual precipitation r_s = –0.600 (Twardosz 1995), the negative trend for the number of days with precipitation is much weaker.

The variability in the annual number of days with precipitation is most of all the result of changes in the number of days with precipitation in half-year periods and seasons (Fig. 2). The strongest trends were observed in the cold half-year period (r_s = 0.286) and in winter (r_s = 0.357), a fact also confirmed in the lines of trends. In contrast, decreasing trends, though much weaker, occurred in the warm half-year period (r_s = –0.144) and in summer (r_s = –0.155). In spring and autumn the number of days with ≥ 0.1 does not show any trend at all.

NUMBER OF DAYS WITH PRECIPITATION ≥ 1 MM AND ≥ 10 MM IN THE 1850–1995 PERIOD

The number of days with precipitation for a higher threshold of total precipitation shows much more variability in various statistical parameters in all the periods considered. The overall decrease in the average, maximum and minimum values is coupled with an increase in the values of the variability coefficients (Table 2).

TABLE 2. Statistical parameters of the number of days with precipitation ≥ 1 mm and ≥ 10 mm in Krakow (1850-1995)

	Mean		Max.		Min.		V (%)	
	≥ 1	≥ 10	≥ 1	≥ 10	≥ 1	≥ 10	≥ 1	≥ 10
year	108.4	17.3	144	30	80	7	11.3	25.4
cold half-year	49.6	3.7	72	16	30	0	17.7	64.0
warm half-year	58.9	13.7	85	23	35	5	16.1	28.0
spring	26.9	3.6	47	9	10	0	23.7	58.4
summer	32.3	8.5	50	19	16	2	20.7	36.6
autumn	24.6	3.9	40	11	9	0	24.8	57.9
winter	24.6	1.3	43	8	13	0	25.2	104.0

v — variability coefficient.

In the case of the annual number of days with precipitation ≥ 1 mm, the average value drops to 108.4, which constitutes about 30 per cent of all days. For the 10 mm threshold it drops to as little as 17.3 per cent, or about 5 per cent of all days. The semi-annual averages of the number of days with precipitation ≥ 1 mm and ≥ 10 mm are markedly higher (by an average of 10 days) in the warm half-year period compared with the cold half. Among seasons, the highest average numbers of days with precipitation occur in summer and the lowest in winter.

The maximum number of days with precipitation ≥ 1 mm (144) was recorded in 1853, and the minimum (80) in 1858. The number of days with precipitation (≥ 10 mm ranges from 30 in the year 1855 to 7 in 1993.

The maximum and minimum numbers of days with precipitation ≥ 1 and ≥ 10 mm in the warm half-year period are higher compared with the cold half-year period. In summer they assume the highest values and in winter the lowest.

Variability in the number of days with precipitation ≥ 1 mm for the year and for the warm half-year period is markedly lower compared with the variability in the number of days with ≥ 0.1 mm. In the remaining periods, the values of variability coefficients are higher. At the same time, the maximum and minimum variability occur in different seasons. Thus, the seasonal values for variability indicate that the highest variability is characteristic of winter and the lowest in summer.

The long-term record of annual number of days with precipitation (≥ 1 mm (Fig. 3) corresponds with changes in total precipitation (r = 0.709). There are three distinct periods with high numbers of days with precipitation, i.e. the end of the 19th century and the first two decades of the 20th century, the late 1930s and early 1940s and the 1960s, as well as five periods with low values, i.e. the 1850s, 1870s and 1880s and next the 1930s, as well as the last period from the year 1970 onwards. The entire series of annual number of days with precipitation shows no trend for changes.

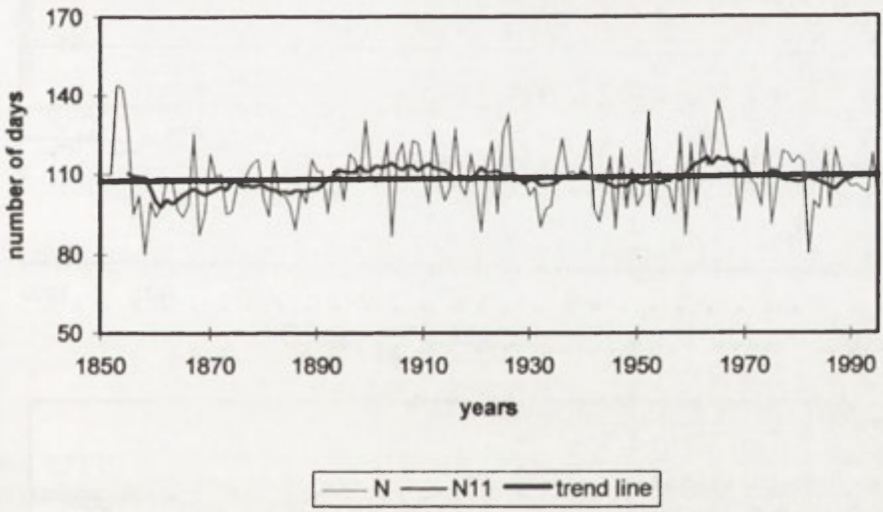

Fig. 3. Long-term variability in the annual number of days with precipitation > 1.0 mm in Krakow (N — values for each year, N11— 11-year moving averages)

The record of changes in the number of days with precipitation > 1 mm correlates best with the changes in the number of such days in the warm half-year period (r = 0.702), the summer (r = 0.605), the spring (r = 0.539) and the cold half-year period (r = 0.502). For the remaining periods, the coefficients are below 0.500.

Up to the end of the 19th century, the numbers of days with precipitation in the warm half-year period were markedly higher than those in the cold half-year period which were particularly evident in the comparison between summer and winter (Fig. 4). Next, since the beginning of the 20th century, there has been a decrease in the range of fluctuations in the number of days with precipitation between the half-year periods and between summer and winter. This results in the occurrence of opposing trends and thus in the cold half-year period (r_s = 0.251) and in the winter (r_s = 0.231) they are positive trends, whereas in the warm half-year period (r_s = –0.190) and in the

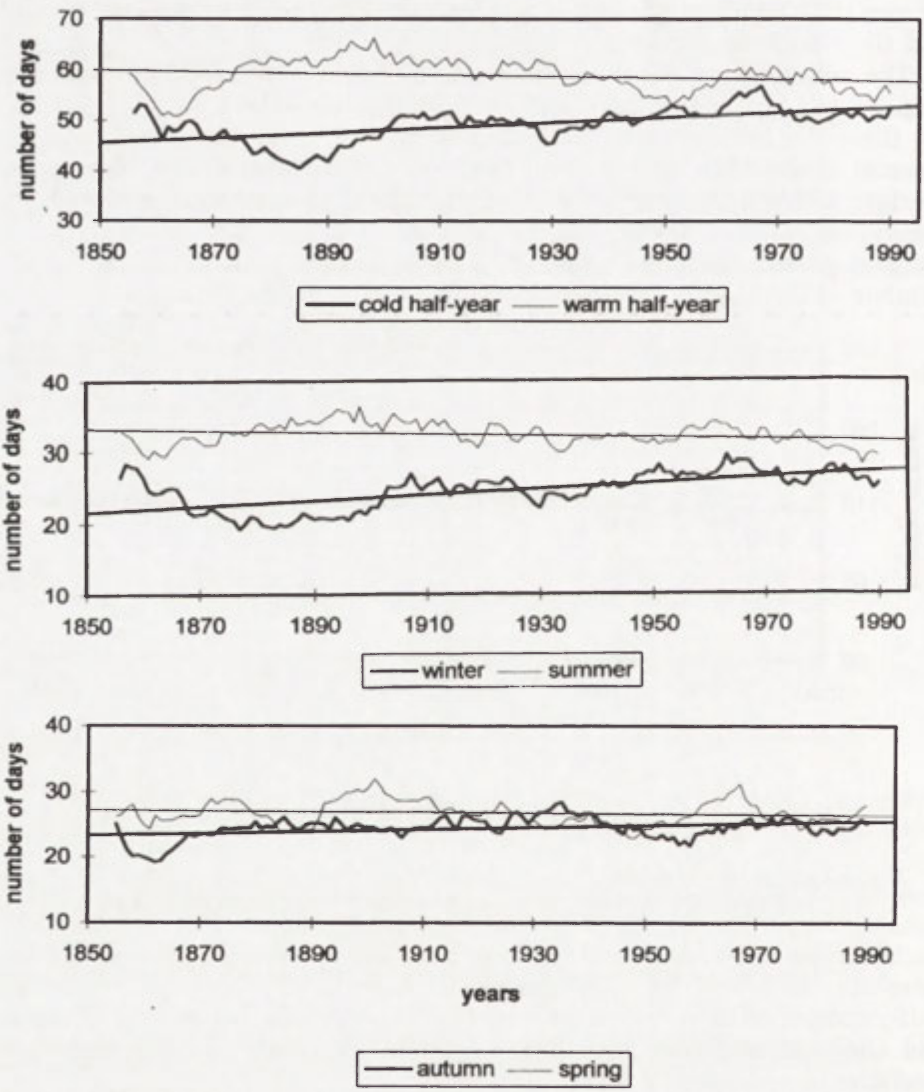

Fig. 4. Long-term course of seasonal 11-year moving averages and trend line for the number of days with precipitation > 1.0 mm in Krakow

summer (r_s = –0.210) they are negative. The number of days with precipitation ≥ 1 mm in spring and autumn does not show any changes throughout the whole of the series. Beginning in the 1970s, a marked decrease in their variability occurred.

The record of the annual number of days with precipitation ≥ 10 mm differs from others in having the highest variations year after year (Fig. 5). The record of the number of days with precipitation in the warm half-year period (r = 0.859) and, to a lesser extent, in the summer period (r = 0.678) correspond directly with it. For the entire annual or semi-annual and seasonal numbers of days with precipitation ≥ 10 mm no trend in changes were detected. It is worth noting that in this case there was a very sharp downward trend in the years 1970–1993.

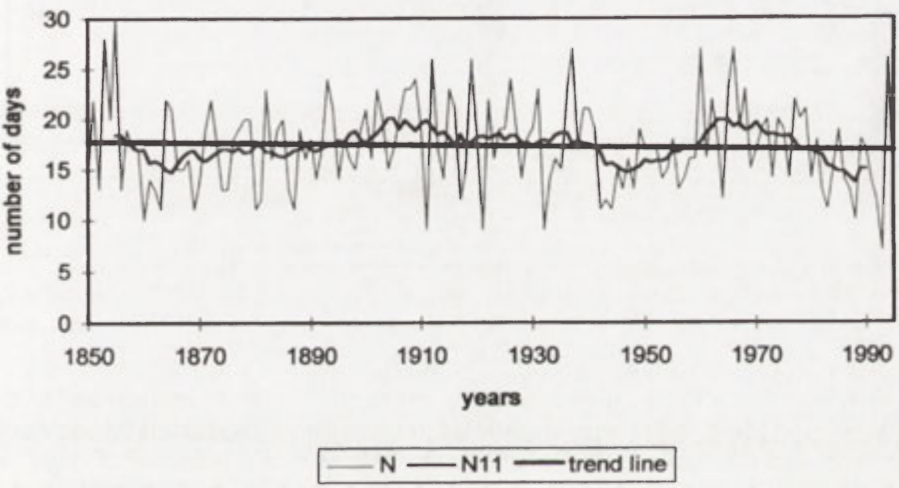

Figure 5. Long-term variability in the annual number of days with precipitation ≥ 10 mm in Kraków (N — values for each year, N11— 11-year moving averages)

THE EFFECT OF CIRCULATION FACTORS ON THE NUMBER OF DAYS WITH PRECIPITATION

The generally-accepted opinion that atmospheric circulation plays a decisive role in climatic changes allows for the assumption that the variability in the number of days with precipitation remains in a close relationship with circulation conditions. This relates in particular to the C index, which was found by some studies to affect precipitation most (Niedźwiedź 1993a).

The average annual value of the C index is –60, which means that the upper Vistula basin region is more often under the influence of anticyclonic systems than cyclonic ones. The consecutive 11-year averages indicate fluctuation of this index, and the line for this trend an increase (Fig. 6).

A preponderance of years with positive index values occurred only in the 1963–1976 period, with the maximum value (102) in 1970. In 1921, the index reached its lowest value (–228). Changes in this index showed a gradual increase till the year 1970, except for the 1920s and the late 1940s, and next a decrease to the –142 level in 1990.

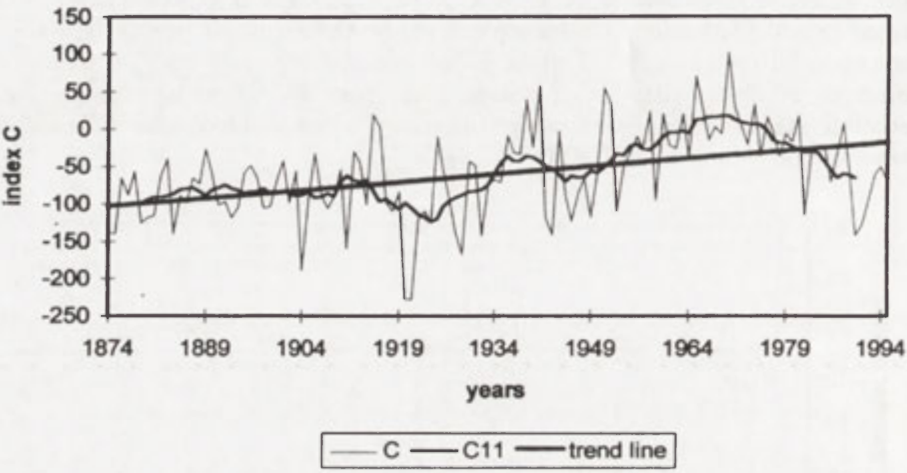

Fig. 6. Long-term variability in the annual values of the cyclonicity index C in southern Poland (C — values for each year, C11— 11-year moving averages) according to T. Niedwiedź (1993b)

The long-term fluctuations of the C index most affect the number of days with precipitation ≥ 0.1 mm and ≥ 1.0 mm. From the statistical viewpoint, all the calculated correlation coefficients between the number of days with precipitation for years, half-year periods and seasons and the C index for the 1874–1995 series are significant at the 0.05 level (Table 3 and 4). In all these cases they are positive. A closer correlations appears between the C index and the number of days with precipitation ≥ 1.0, with a highest value of 0.631 in the cold half-year period. In the case of the number of days with precipitation ≥ 0.1, the highest index (0.557) occurs in spring.

Variability in the number of days with precipitation shows higher sensitivity to the fluctuations of the C index than precipitation totals. The coefficients for correlations between precipitation and cyclonicity calculated for an analogous period are lower and only in winter do they exceed the value r = 0.500 (Niedźwiedź 1993a).

It was found that in individual normal periods the annual number of days with precipitation > 0.1 and > 1.0 mm reached much higher correlation coefficients with the C index against the background of the entire 1874–1995 series. The values of these coefficients reach 0.634 in the period 1901–1930 (Table 3) and 0.622 in the period 1931–1960 (Table 4). In a prevailing number of cases, higher coefficients were also found in particular half-year periods and seasons. Thus, for the 0.1 mm threshold, the maximum coefficient (0.756) was calculated for spring in the period 1931–1960, the next (0.730) for summer and 0.670 for the cold half-year period for the years 1901–1930 (Table 3). For the 1.0 mm threshold the highest value (0.746) was found for autumn, along with 0.730 for summer in the same 1901–1930 period (Table 4).

TABLE 3. Correlation coefficients between the number of days with precipitation >0.1 mm and cyclonicity index C

	1874-1995	1901-1930	1931-1960	1961-1990
year	0.351	0.634	0.516	0.453
cold half-year	0.485	0.670	0.499	0.467
warm half-year	0.360	0.645	0.614	0.546
spring	0.557	0.565	0.756	0.509
summer	0.430	0.730	0.476	0.377
autumn	0.374	0.589	0.547	0.541
winter	0.405	0.501	0.419	n.s.

n.s. — not significant at the 0.05 level.

TABLE 4. Correlation coefficients between the number of days with precipitation > 1 mm and cyclonicity index C

	1874-1995	1901-1930	1931-1960	1961-1990
year	0.461	0.584	0.622	0.560
cold half-year	0.631	0.685	0.689	0.605
warm half-year	0.445	0.663	0.582	0.602
spring	0.518	0.441	0.598	0.502
summer	0.425	0.730	0.414	0.365
autumn	0.587	0.746	0.691	0.537
winter	0.536	0.582	0.561	0.488

CONCLUSIONS

The analysis of the number of days with precipitation in a long-term perspective reveals the presence of fluctuations conditioned by variability in the circulation factor. These fluctuations are marked by greater irregularities when compared with the precipitation totals. On an annual scale, neither the number of days with precipitation nor the precipitation totals show any trends. In both cases, trends appear on the seasonal scale which allow for mention of a major conformity between the changes in these two elements. This may be of major importance to further research, particularly on the scale of Central Europe with its very asynchronous precipitation changes. Changes in precipitation in this region of Europe are affected mainly by high daily precipitation values (over 10 mm). Such precipitation values occur relatively rarely and thus do not affect changes in the number of days with precipitation. The occurrence of such precipitation is also affected, apart from by circulation factors, by local factors. There is reason to believe that studies on spatial differentiation in the number of days with precipitation at determined threshold values, which show more sensitivity to changes in circulation and are less liable to the effects of local factors, will allow better information on the variability in the precipitation regime in this region. It will also facilitate the reconstructing and forecasting of disastrous climatic phenomena in the region, particularly floods.

The study has shown that the changes in the number of days with precipitation $\geq$ 0.1 mm and $\geq$ 1.0 mm in Kraków present significant positive trends in the cold half-year period and in winter, and negative trends in the warm half-year period and summer. The variability in the number of days with precipitation is significantly correlated with the fluctuations of the cyclonicity index C — a phenomenon which is most strongly apparent in the cold half-year period.

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THERMAL DIFFERENTIATION OF WINTERS IN THE CARPATHIAN MOUNTAINS ALTITUDINAL PROFILE DURING THE PERIOD 1961/62–1990/91

Katarzyna Piotrowicz
Department of Climatology, Institute of Geography of the Jagellonian University
ul. Grodzka 64, 31-044 Krakow, Poland

ABSTRACT: The paper attempts an evaluation of winter thermal differentiation in the Carpathian altitudinal profile in relation to some external and internal factors of the montane climatic system. Mean monthly, mean daily and daily maximum air temperatures were taken, for three stations representing different altitudinal climatic zones, in the period 1961/62–1990/91. The variability of the dates of winter commencement and end, winter duration and thermal indices were analysed, as was the relation between the occurrence of frosty days and atmospheric circulation characteristics. The biggest decrease in the examined period was observed for the numbers of winter days and frosty days in Zakopane and Krakow, while at Kasprowy Wierch mountain the number of winter days increased slightly and the number of frosty days decreased. It was established that winter thermal conditions at Kasprowy Wierch depend above all on air circulation and advection conditions in the free atmosphere, while at the two other stations, located in urban areas, anthropogenic factors interfere with natural climate changes.

KEY WORDS: winter, air temperature, Carpathian Mountains, climatic vertical zones.

INTRODUCTION

The problem of air temperature variability in the Carpathian Mountains has been presented in rather few papers, e.g. those W. Milata (1938), E. Michna and S. Paczos (1987/88), and of the climatologists from Kraków: M. Hess (1965), M. Hess et al. (1977), T. Niedźwiedź (1981), B. Obrębska-Starklowa et al. (1995) and J. Trepińska (1995). Most of these studies were based on mean annual or mean monthly values for air temperature, while papers presenting the problem of thermal winters either did not consider the highest part of the Carpathian Mountains or based their analysis on short-term observations or multi-year values. The works in question are those of W. Wiszniewski (1960), A Kosiba (1954, 1956), M. Hess (1965),

S. Paczos (1982), J. Trepińska (1971, 1976), T. Niedźwiedź and D. Limanówka (1992), H. Lorenc and M. Suwalska-Bogucka (1995).

The duration of winter in Poland is one of the winter characteristics experiencing distinct oscillations in its interannual course. As A. Kosiba (1956) stated, winter is the best indicator of climate changes, as it is mainly its temperatures that influence mean annual value for air temperature.

The results of research carried out so far in the Carpathian Mountains by the Department of Climatology, Institute of Geography, Jagellonian University, show an upward trend for mean winter temperature (for standard winter: Dec.–Feb.), which is slightly weaker in the highest part of the mountains (characterized by a more stable climate resulting from the domination of atmospheric circulation).

The aim of this paper is to attempt an evaluation of thermal winter conditions in the altitudinal profile of the Carpathian Mountains and to demonstrate the utility of different thermal indices for this purpose. As it continues the author's research on winter thermal conditions (Piotrowicz 1994, 1996), the results may be considered another approach to the problem and may be used for climate reconstructions.

SOURCE MATERIALS AND METHODS

The data used to analyse winters in the altitudinal profile of the Carpathian Mountains were: mean monthly, mean daily and daily maximum values of air temperature for the years 1961/62–1990/91, recognized by WMO as a standard period for climatological research. The data come from three stations:

— Kasprowy Wierch mountain, Tatra Mts. ($\varphi = 49^o14'$ N, $\lambda = 19^o59'$E, h = 1991 m a.s.l.),

— Zakopane ($\varphi = 49^o18'$N, $\lambda = 19^o57'$E, h = 857 m a.s.l.),

— Kraków ($\varphi = 50^o04'$N, $\lambda = 19^o58'$E, h = 206 m a.s.l.).

The analysed period seems to be representative for winter variability research, as it includes both very severe winters: 1962/63, 1963/64, 1967/68 and very mild ones: 1974/75, 1988/89, 1989/90 (Paczos 1982, Lorenc, Suwalska-Bogucka 1995, Piotrowicz 1996).

The stations are located at the same longitude — 19°E, in different forms of relief and in different vertical climatic zones of the Carpathian Mountains (Hess 1965): Kraków at the lower border of the warm temperate zone, Zakopane in the cool temperate zone and Kasprowy Wierch in the cold temperate zone. Additionally, both Kraków and Zakopane are situated in basins, each lying evenly with a parallel of latitude.

Thermal seasons in Poland are traditionally determined by reference to the crossing of certain mean daily temperature thresholds. Winter is the period with mean daily temperature < 0°C. However, determining the dates of its commencement and end is rather difficult and ambiguous (Piotrowicz 1996).

The following indices were used in this research to show thermal differentiation of winters:

— dates of the commencement and end of winter together with its duration, determined on the basis of mean monthly air temperature,

— dates of the commencement and end of winter, determined on the basis of mean daily air temperature; with winter beginning on the first day with mean daily temperature < 0°C and ending on the last such day,

— the number of: winter days (mean daily air temperature < 0°C), frosty days (daily maximum air temperature < 0°C) and the sums of frost (sums of mean daily air temperature < 0°C).

Atmospheric circulation is the main factor determining the differentiation of air temperature in the mountains, together with the elevation a.s.l. and the relief forms. The types of synoptic situation from T. Niedźwiedź (1988, 1992) for the upper Vistula river basin have therefore been used, together with the index of cyclonicity (C) (Niedźwiedź 1993).

THE DATES OF THE COMMENCEMENT AND END OF WINTER. WINTER DURATION

The dates of the commencement and end of winter, determined on the basis of mean monthly air temperature (Table 1), prove that in the period 1961–90 at Kasprowy Wierch mountain, the season usually started as soon as the middle of October, one month later in Zakopane, and as late as the middle of December in Kraków.

TABLE 1. Mean dates of winter's commencement, end and duration at Kasprowy Wierch Mt in Zakopane and Kraków in the 30-year periods 1961–1990 and 1951–1980

Station	1961–1990			1951–1980*		
	beginning	end	duration	beginning	end	duration
Kasprowy Wierch Mt	22.10	1.05	190	22.10	3.05	192
Zakopane	23.11	16.03	112	24.11	18.03	113
Kraków	12.12	21.02	70	no data available		

* after T. Niedźwiedź and D. Limanówka (1992).

The season ended earliest in Kraków (21st Feb.), it usually lasted 23 days more in Zakopane (until 16th March) and would end on 1st May at Kasprowy Wierch.

The same indices — and the duration of winter calculated by the same method but for the period 1951–1980 — are also shown in Table 1 (Niedźwiedź and Limanówka 1992). Mean dates of winter commencement are very similar to those presented before or differ by one day, while the dates of the end are shifted by two days; the differences are very little. Unfortunately, such a comparison cannot be made for Kraków, as the standard meteorological station with the shelter at 2 m above ground level was organized in 1958. The data gathered at the station before 1958, in the shelter placed 12 m above ground level (the historical station) cannot be used, as this would cause inhomogeneity of the series.

Mean dates for the commencement and end of winter, together with winter duration, determined on the basis of mean monthly air temperature for six 5-year periods were also analysed (Table 2), and compared with the mean values for the 30-year period (Table 1). The longest winters occurred:

— in Kraków in the period 1961–65; usually lasting for 92 days, starting about a week earlier than mean winters in the 30-year period, and ending about 2 weeks later,

— in Zakopane in the period 1966–70; lasting 151 days on average, starting on 24th Nov. (1 day earlier than in the 30-year period), and ending about a month and half later (25th April) than in the 30-year period (16th March),

— at Kasprowy Wierch in the period 1971–75; usually lasting 205 days, starting on 7th Oct. (2 weeks earlier than in the 30-year period) and ending similarly as in the 30-year period — on 1st May.

TABLE 2. Mean dates of winter's commencement, end and duration at Kasprowy Wierch Mt, in Zakopane and Kraków in the 5-year periods in 1961–90

years	Kasprowy Wierch Mt			Zakopane			Kraków		
	beginning	end	duration	beginning	end	duration	beginning	end	duration
1961–65	26.10	30.04	185	23.11	21.03	117	4.12	7.03	***92***
1966–70	29.10	28.04	**180**	24.11	25.04	***151***	6.12	15.02	70
1971–75	7.10	1.05	***205***	18.11	8.03	**109**	12.01	3.02	**21**
1976–80	25.10	8.05	194	25.11	16.03	**110**	14.12	22.02	69
1981–85	22.10	30.04	189	21.11	14.03	112	2.01	25.02	53
1986–90	23.10	27.04	185	20.11	17.03	116	12.01	4.02	22

The longest winters occurred the earliest in the Carpathian Foreland and then gradually started in higher parts of the mountains. The shortest winters occurred in Kraków in the period 1971–75, they lasted only for 21 days, three times shorter than usually in the 30-year period (Table 1). They started as late as in the middle of January (12th Jan.) and ended at the beginning of February (3rd Feb.). They occurred in Kraków at the same time as the longest winters at Kasprowy Wierch did. In Zakopane, short winters occurred in the whole 10-year period 1971–80, but they were only shorter by 2 or 3 days than mean winter of the 30-year period. In the first 5-year period (1971–75) they started earlier by 5 days and ended earlier by 8 days, while in the second period (1976–80) they started 2 days later and ended as in the 30-year period (16th March). At Kasprowy Wierch, the shortest winters of the period 1966–70 preceded the longest ones (1971–75). The winters of 1966–70 usually lasted 180 days (10 days less than average ones and 25 days less than the longest ones). They started on 29th October and ended on 30th April. In the case of the longest winters a shift may be observed in the altitudinal profile of the Carpathian Mountains, while time correlation in the occurrence of the shortest winters in the Tatra Mts. in the period 1961–90 can hardly be seen. The correlation is stronger for lower vertical climatic zones.

The dates of winter commencement and end determined in 5-year periods on the basis of mean monthly air temperature do not show interannual variability. As S. Paczos (1982) stated, it is much more appropriate for this purpose to calculate the dates of the so-called "specific winter" (Kosiba 1956) or "real winter" (Mitosek 1961). In the author's opinion there is no explicit criterion for determining that season's limits, as it is very difficult to define when the prevalence of days with mean daily temperature < 0°C occurs (Piotrowicz 1996). The analysis was therefore carried out for the winter period with the beginning on the first day with mean daily air temperature < 0°C and the end on the last such day. Such a definition of extreme dates allows for the analysis of all winter days which occurred in the examined period and are characteristic for winters in Poland and Central Europe.

The first days with mean daily temperature < 0°C in the 30-year period occurred on average after: 23rd Aug. at Kasprowy Wierch, 30th Oct. in Zakopane and 17th Nov. in Kraków. Their largest interannual fluctuations were observed for Kasprowy Wierch (variability coefficient 62.4 per cent, for Zakopane 10.9 per cent, for Kraków 11.0 per cent), as such days appeared there as early as 1st July (1974) and as late as 9th Sep. (1982). First winter days occurred in Zakopane from the beginning of October (3rd Oct. 1972) to the middle of November (21st Nov. 1963), while in Kraków from 21st Oct. (1976) to 9th Dec. (1974).

In the examined 30-year period the last winter days occurred on average on 12th June at Kasprowy Wierch, on 20th April in Zakopane and on 13th March in Kraków, but extreme cases were:

— at Kasprowy Wierch: the earliest on 14th May 1979, the latest on 30th June 1962,

— at Zakopane: the earliest on 3rd April 1966, the latest on 12th May 1978,

— at Kraków: the earliest on 14th January 1989, the latest on 13th April 1986.

The largest fluctuations were therefore observed for the date of winter commencement at Kasprowy Wierch and the date of winter's end in Kraków. The correlation coefficients calculated for the dates of winter commencement and end showed the strongest correlation between the dates of winter's end at Kasprowy Wierch and Zakopane (0.625).

NUMBER OF WINTER DAYS, FROSTY DAYS AND SUMS OF FROST

The average number of winter days in the examined period was: 191 for Kasprowy Wierch, 100 for Zakopane and 60 for Kraków. The highest values occurred during winter 1990/91 at Kasprowy Wierch — 218 days, during winter 1962/63 in Zakopane — 121 days and in Kraków — 96 days (Fig. 1). The lowest number of days with mean daily temperature < 0°C characterized the winters of: 1982/83 at Kasprowy Wierch –161 days, 1989/90 in Zakopane — 65 days and 1974/75 in Kraków — 23 days. The values did not show significant fluctuations in the examined period for Kasprowy Wierch (variability coefficient 0.7 per cent), while their number diminished considerably in both Zakopane (by 17 days) and Kraków (by 21 days). The correlation coefficient calculated for the number of winter days at all stations was highest for Zakopane and Kraków (0.665).

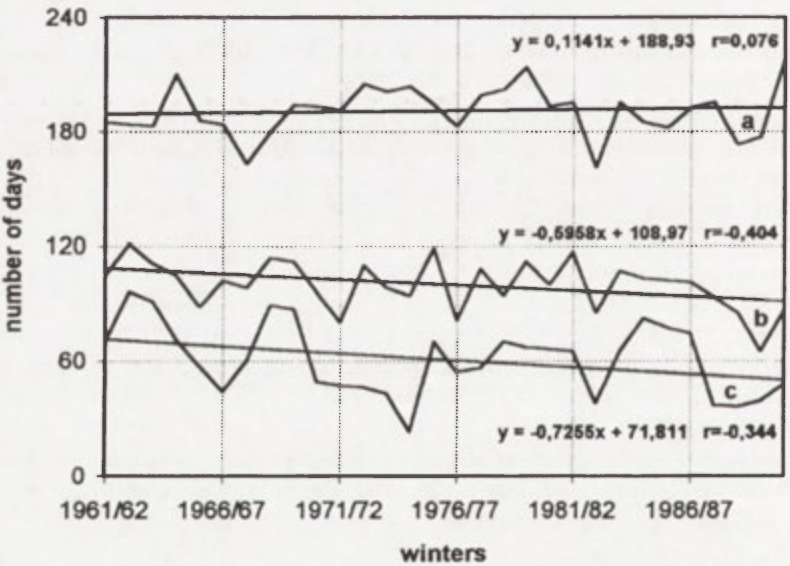

Fig. 1. The course of the number of winter days and trend lines for Kasprowy Wierch (a), Zakopane (b) and Krakow (c) in the period 1961/62–1990/91
x — year, y — number of days, r — correlation coefficient

M. Hess (1965) analysed the period 1952–61 and stated that the mean number of frosty days in the Carpathian Mountains changes over a large range, from 30 in the foreland up to 200 in the highest parts of the Tatra Mountains.

The mean numbers of frosty days in the period 1961/62–1990/91 were 148 at Kasprowy Wierch, 53 in Zakopane and 33 in Krakow. The greatest variability was observed for Krakow, from 4 days during winter 1974/75 up to 68 days in 1962/63 (variability coefficient 51.2%). The number of frosty days, like the number of winter days, decreased by 21 days at that station during the examined period (Fig. 2). The variability coefficient for frosty days had a lower value for Zakopane (27.8 per cent), but the course was similar to the one for Kraków. The correlation coefficient for the number of frosty days in Zakopane and Kraków was 0.826. The highest values were noted for winter 1962/63 — 82 days, the lowest in 1972/73 — 23 days. As the trend line shows (Fig. 2), the number of frosty days diminished in the examined period by 18 days.

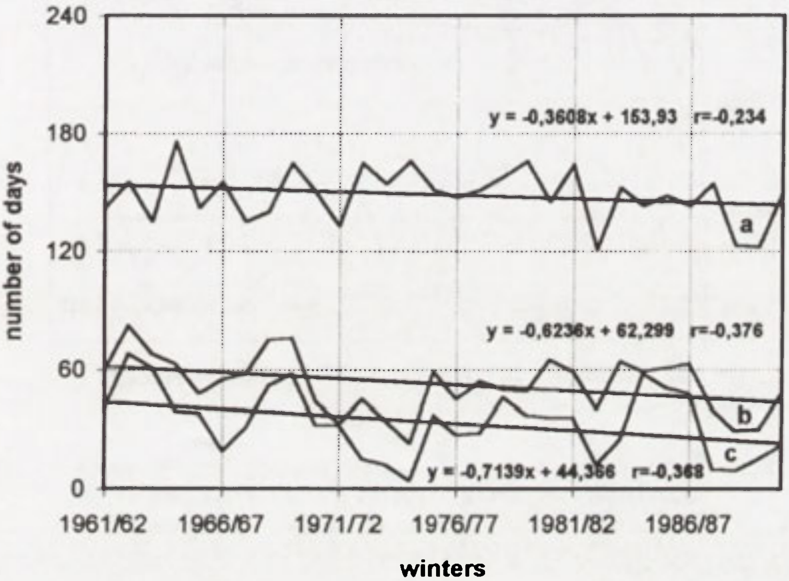

Fig. 2. The course of the number of frosty days and trend lines for Kasprowy Wierch (a), Zakopane (b) and Kraków (c) in the period 1961/62–1990/91
x — year, y — number of days, r — correlation coefficient

The course of frosty days at Kasprowy Wierch is very interesting (Fig. 2). In the period 1961/62–1990/91 there were on average 148 such days and the values varied from 121 days (1982/83) to 176 (1964/65). A slight decrease in the index (of 10 days) can be observed in the examined period, contrary to the increase in the number of winter days.

For the sums of frost the correlation coefficients were: 0.935 between Zakopane and Kraków, 0.594 between Kasprowy Wierch mountain and Zakopane and 0.477 between Kasprowy Wierch and Kraków. Mean values for sums of frost for the period 1961/62–1990/91 were –1188.3°C for Kasprowy Wierch, –517.5°C for Zakopane and –275.1°C for Kraków. The values changed in the following ranges: from –872.6°C (1989/90) to –1474°C (1962/63) for Kasprowy Wierch, from –281.4°C (1974/75) to –966.0°C (1962/63) in Zakopane and from –45.2°C (1974/75) to –723.4°C (1962/63) in Kraków (Fig. 3). According to this criterion, the most severe winter in the whole altitudinal profile was 1961/62 and the mildest 1974/75, but only in the lower vertical climatic zones.

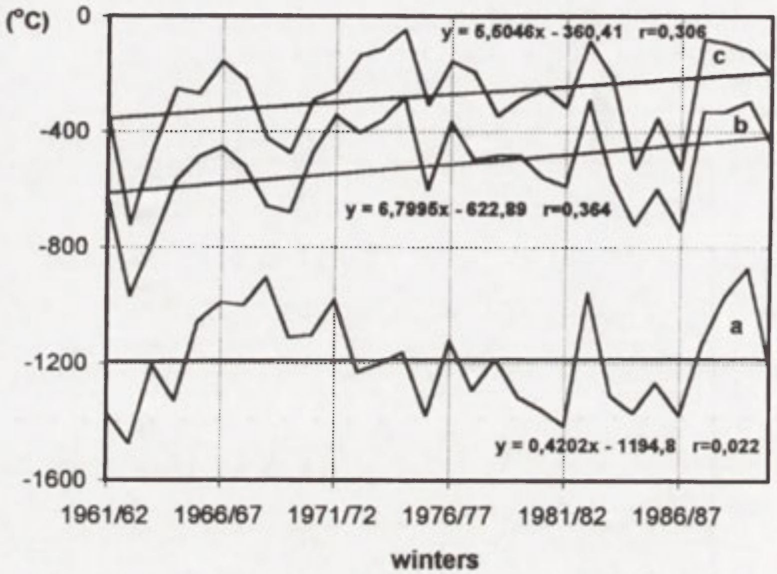

Fig. 3. The course of the sums of frost values (°C) and trend lines for Kasprowy Wierch (a), Zakopane (b) and Krakow (c) in the period 1961/62–1990/91
x — year, y — number of days, r — correlation coefficient

RELATIONS BETWEEN THE NUMBER OF FROSTY DAYS AND TYPES OF SYNOPTIC SITUATION

The decrease in the number of frosty days at Kasprowy Wierch in the examined period made the author seek an explanation for this phenomenon. A comparison was therefore made between the occurrence of frosty days and the different synoptic situations according to the calendar worked out by T. Niedźwiedź (1988, 1992).

Frosty days occurred most often at Kasprowy Wierch (19.2 per cent) during an air mass advection from the West, both in cyclonic and anticyclonic situations (W_a, W_c) (Table 3). Those days occurred most often in Zakopane (18.5 per cent) and Kraków (22.3 per cent) during an air mass advection from the East (E_a, E_c). A relatively high frequency of frosty days occurred at all stations during situations with no advection (K_a), or with advection from different directions (B_c).

TABLE 3. The frequency (in %) of particular circulation types during the occurrence of frosty days at Kasprowy Wierch, in Zakopane and Kraków in the period 1961/62–1990/91 (Niedźwiedź 1988, 1992)

	Kasprowy Wierch	Zakopane	Kraków
N_a, N_c	6.8	8.8	6.9
NE_a, NE_c	6.1	9.3	8.5
E_a, E_c	9.6	**18.5**	**22.3**
SE_a, SE_c	7.5	8.3	13.2
S_a, S_c	7.5	3.9	6.3
SW_a, SW_c	7.9	3.7	3.6
W_a, W_c	**19.1**	11.4	5.3
NW_a, NW_c	12.9	11.7	6.4
C_a, C_c	4.0	4.4	6.3
K_a, B_c	**15.6**	**16.9**	**18.0**
X	2.9	3.2	3.2
anticyclonic	45.5	59.1	65.7
cyclonic	51.6	37.7	31.1

N, NE, ... — directions of advection; a — anticyclonic; c — cyclonic;
C_a — central anticyclonic situation, advection lacking, high over southern Poland;
C_c — central cyclonic situation, centre of low over southern Poland;
K_a — anticyclonic wedge, sometimes several indistinct high centres or a neutral pressure field of relatively higher pressure, axis of the ridge of high pressure;
B_c — trough of low pressure, neutral field of low pressure or the axis of the trough with varying directions of air flow and frontal system;
X — unclassified situations and pressure cols.

The data showing the frequency of occurrence of frosty days in relation to anticyclonic and cyclonic situations were also presented in Table 3. Those days occur most often (51.6 per cent) during cyclonic situations only at Kasprowy Wierch. At other stations, representing concave land forms, higher frequencies accompany anticyclonic situations. The diminishing number of frosty days at Kasprowy Wierch can therefore be related to changes in atmospheric circulation and the location of the station in the highest part of the Tatra Mts. Additionally, the index of cyclonicity (C) was calculated following the method of T. Niedźwiedź (1993) for the cold half-year (November–April) (Fig. 4). The trend line shows a large decrease in the value of the index, statistically significant at the 5 per cent level (correlation coefficient 0.5). In the examined period, a slight decrease of frosty days on Kasprowy Wierch took place and there was a parallel increase in the share of synoptic situations unfavourable for their occurrence. The results may prove that change in winter's character (the occurrence of mild winters) in higher vertical climatic zones might increase during periods of intensified cyclonic situations and an air advection from the West. Those changes have already occurred in lower vertical climatic zones represented by Zakopane and Kraków, but are much more visible for Kraków, where anthropogenic factors interfere with natural climatic change. Zakopane seems to be a transitional station, as the courses of some characteristics (e.g. the dates of winter's end) are similar to those of Kasprowy Wierch mountain, while others (e.g. the number of winter days) resemble a station in an upland, located in an urban area.

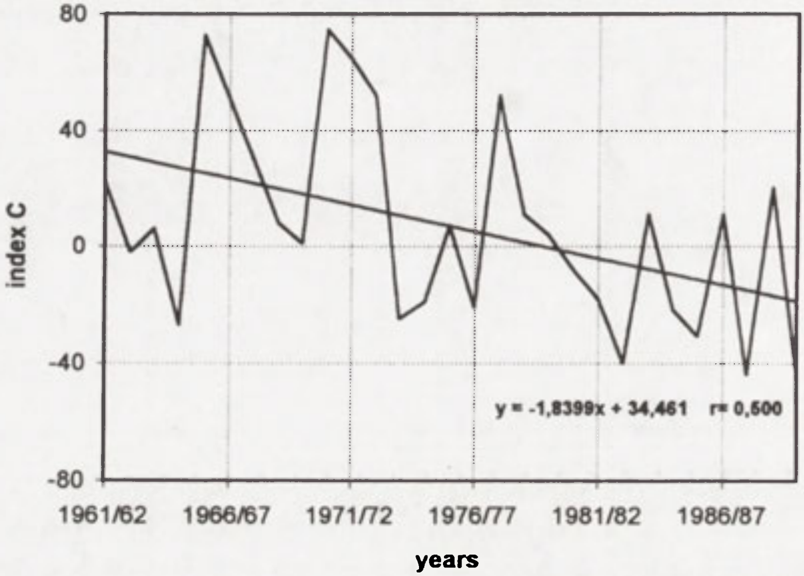

Fig. 4. The course of circulation index C over southern Poland in the cold half-year (November–April) in the period 1961/62–1990/91
x — year, y — number of days, r — correlation coefficient

CONCLUSIONS

The standard climatological period 1961/62–1990/91, analysed in the present paper, is too short to allow for the evaluation of regularities in the thermal variability of winters in the altitudinal profile of the Carpathian Mountains. The period is however representative for climatic research as both very mild and very severe winters occurred in it. The regularities stated for the examined years may therefore be extrapolated for earlier periods and can serve as a certain model for climatic reconstructions. They also show differences in the climate sensibility character between lower and higher vertical climatic zones — the latter is exposed to only a very limited impact of the geographical environment and man.

Thermal conditions of winters at Kasprowy Wierch depend on different factors (e.g. changed atmospheric circulation conditions) than at the two other stations, located in basins, where natural changes are influenced by anthropogenic factors.

The analysis of winter thermal differentiation in the altitudinal profile of the Carpathian Mountains, attempted in this paper, leads to the following conclusions:

— the dates of winter's commencement and end, determined on the basis of mean monthly air temperatures for the 30-year period and 5-year periods were most variable in the warm temperate vertical climatic zone and least variable in the cold temperate one,

— the longest winters occurred earliest in the Carpathian Foothills (Kraków), in the period 1961–65, and in higher parts of the Carpathians in the following 5-year periods (Zakopane 1966–70, Kasprowy Wierch mountain 1971–75),

— the shortest and mildest winters (with lowest values for the numbers of winter days, frosty days and sums of frost) occurred in Kraków and Zakopane in the first half of the 1970s and in the second half of the 1980s. The shortest winters in the foothills in the 1970s were accompanied by the longest winters at Kasprowy Wierch,

— the values for sums of frost were characterized by the highest correlation coefficients for all stations: Zakopane–Kraków 0.935, Kasprowy Wierch–Zakopane 0.594, Kasprowy Wierch Mt–Kraków 0.477. For other thermal indices high correlation coefficients, significant at the 0.05 level, occurred between Zakopane and Kraków, both for frosty days (0.826) and for winter days (0.665),

— frosty days occurred most often at Kasprowy Wierch during cyclonic situations and an air advection from the West, while in Zakopane and Kraków during anticyclonic situations and an air advection from the East. This attests to the prevailing role of relief and the occurrence of thermodynamic atmospheric stability in establishing thermal conditions in lower vertical climatic zones,

— sums of frost and the number of frosty days are the two most useful indices in the evaluation and reconstruction of winter-period climate changes.

The obtained results show the necessity for continuation of the research, above all on the basis of detailed analysis of atmospheric circulation and daily temperature data from more stations, representing different forms of relief.

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VARIABILITY OF THE SOUTH SHETLAND ISLANDS GEOECOSYSTEM

STANISŁAW RAKUSA-SUSZCZEWSKI, ANNA KIDAWA
Department of Antarctic Biology, Polish Academy of Sciences
ul. Ustrzycka 10, 02-141 Warszawa, Poland

ABSTRACT: Variability is one of the characteristic features of polar geoecosystems. On the meso- and macro-time scales, the variability of geoecosystems can be expressed in relation to: irregular interannual changes, multi-year cyclic changes, year-to-year directional changes and anthropogenic changes. Polish multidisciplinary research concerning the physical, chemical and biological processes in the region of Admiralty Bay (King George Island, South Shetland Islands) demonstrates such variability.

KEY WORDS: variability, geoecosystem, South Shetland Islands, climate change.

INTRODUCTION

The functioning of polar geoecosystems, as we are ever better coming to understand, is subject to conditions of feedback with geoecosystems on a global scale (Ackley *et al.* 1996). This is of special importance in the case of Antarctic.

Polar geoecosystems are stable and elastic but impermanent, as they show more or less explicit differences if the same season of the year is compared over long periods (Remmert 1980).

The variability of geoecosystems relates to physical, chemical and biological processes.

A unique feature of polar geoecosystems is their considerable temporal variability expressed in:

— changes occurring irregularly year by year,
— long-term cyclical changes,
— year-by-year changes progressing in a given direction,
— changes caused by the direct interference of man.

THE VARIABILITY OF BIOLOGICAL PROCESSES AND THEIR CAUSES

In the Antarctic Marine, the seasonality of biological processes, especially trophic relationships and the phenology of species, are under the influence of physical processes of huge energies. This has a decisive impact in relation to inconstancy in geoecosystem function (Remmert 1980), and variability of the processes of matter and energy cycling on time scales of months and years. Interdisciplinary research conducted close to Admiralty Bay provides examples of such variabilities (Fig. 1).

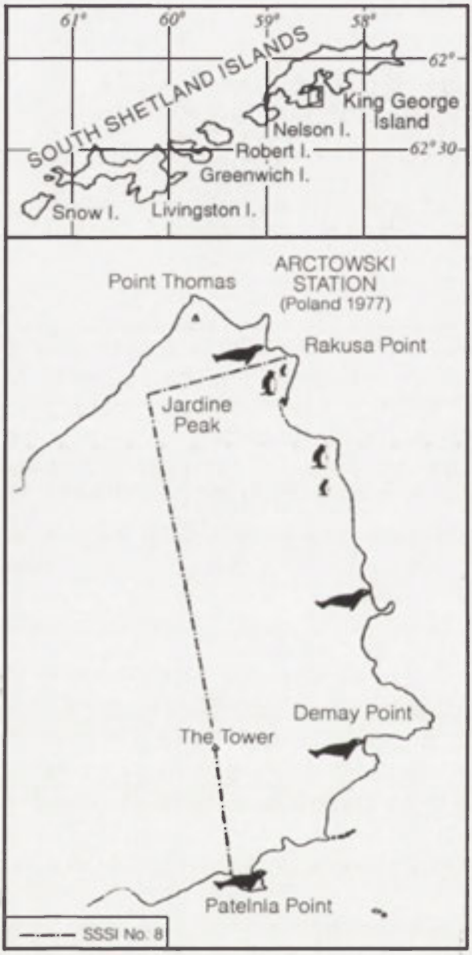

Fig. 1. South Shetland Islands and west coast of Admiralty Bay – Site of Special Scientific Interest No. 8. Main rookeries and wallows of elephant seals are marked

The average air temperature measured at 4 stations located on the South Shetland Islands (Arctowski, Bellingshausen, Eduardo Frei and Arturo Prat) has increased between the end of the 1940s and today (Martianow, Rakusa-Suszczewski 1990, Rodriguez *et al.* 1996) by an average of 1.4°C (from –3.6°C to –2.2°C). The mean annual air temperature at the Arctowski Station in 1981 was –1.2°C which means an increase of about 2.4°C in relation to the 1940s. Similar trends have been observed in the area of Faraday Station located on the Antarctic Peninsula. The air temperature, increased there between the end of the 1940s and the 1990s by an average of 2.5°C (Ackley *et al.* 1996), as shown in Fig. 2. Stations located on the South Shetland Islands also registered a change in the variability range of annual air temperature. Winter minimal temperature tended to increase and maximum summer and autumn temperatures to decrease (Rodriguez *et al.* 1996). In the opinion of Rodriguez, the change in air temperature in the South Shetland Islands is characterized by 5-year periodicity overlapping with the general trend towards climatic warming. However, the change in air temperature in the region of the Antarctic Penninsula and the South Shetland Islands is weakly correlated with air temperature changes over the Antarctic continent (Auckley *et al.* 1996).

The change in air temperature is influencing the temperature of sea water. The annual cycle of air temperature and temperature variations in particular years are reflected in the course of trends for water temperature observed in Admiralty Bay. Sea water temperature observed in winter 1994/95 was distinctly lower than that in 1979 when air temperature had been markedly higher (Rakusa-Suszczewski 1996). A negative correlation exists between air temperature and glacial conditions (Ackley *et al.* 1996). However both

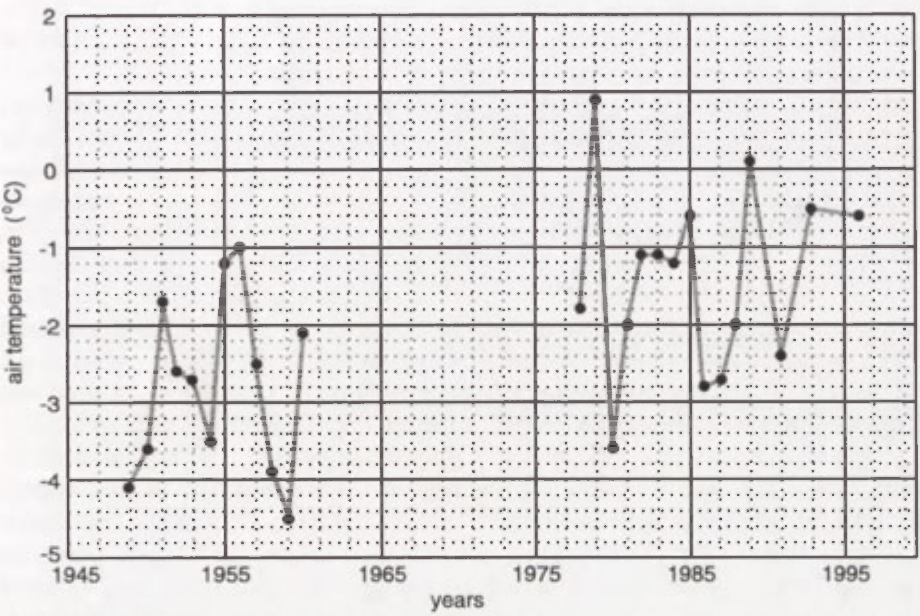

Fig. 2. Average annual air temperature within Admiralty Bay at British Station G in 1949–1960 and of Arctowski station in 1978–1996

ice cover and its durability are characterized by considerable fluctuations. Winter 1985 on the South Shetland Islands was characterized by especially high air temperature, and as a result Bransfield Strait was not yet frozen over even in August (Quetin, Ross 1991). Similarly mild winter occurred in 1989. However during winter 1987 the ice pack extended as far as 150 km north of the South Shetland Islands (Quetin, Ross 1991).

Winter ice cover exerts an influence on feeding conditions for krill (*Euphasia superba*) beneath the ice. This is especially true of its larval phase. (L.B. Quetin *et al.* 1994) observed that during the severe winter of 1987, krill larva: a) developed rapidly, b) contained considerable amounts of lipids and, c) demonstrated a good condition index. In contrast, during the mild winter of 1989, the lipid content of the larvae was low, while larvae were in a bad condition and moreover, shrinking. It may be presumed that changes of the above kinds would have consequences both for the abundance of the krill population and populations of its consumers.

Winter ice conditions presumably also influence the beginning and length of the progenitive period in krill. Abnormal reproduction seasons occur frequently during years with ice anomalies, for example in 1980/81 around the Bransfield Strait, a rapid retreat of marine ice was observed, together with an early and short progenitive period for krill (Spiridonov 1995). It may therefore be presumed that such variation in krill behaviour will be associated with year-on-year changes is feeding conditions. For the rate of phytoplankton growth near to the ice zone is correlated with fluctuations in the range and durability of marine ice, with variations even reaching 50 per cent (Smith *et al.* 1988).

At the same time it has been recorded that, following severe winters, krill are more abundant (Rakusa-Suszczewski 1988), although it is not likely that biological processes such as growth and mortality could explain all the observed variability in population biomass (Godlewska, Rakusa-Suszczewski 1988, Rakusa-Suszczewski 1990). J. Priddle *et al.* (1988) calculated that the extinction of one larval generation of krill can bring about a decrease in the population of up to 36.6 per cent as compared with the previous quantity. However, irregular fluctuations in krill biomass in the area of the Bransfield Strait can reach two orders of magnitude (Kalinowski 1984, Kalinowski *et al.* 1985) and it may be expected that the phenomenon is an outcome of physical factors conditioning krill distribution around the Antarctic continent.

Studies in the northern part of the Bransfield Strait have revealed a sea current from SW to NE, which is active year round but at varied speed. This current moves krill from the west, from the area of the Bellingshausen Sea. As evidenced by observations carried out during the SIBEX research project (1982/83) — an inflow of warm waters from the north to the area of the South Shetland Islands was accompanied by a decrease in krill biomass. It seems that variation in krill biomass around the Bransfield Strait is first and foremost the result of changes in atmospheric circulation which bring about an inflow of water from the north to the Bellingshausen Sea, blocking the sea current from the west abundant in krill. A similar situation has been recognized in other parts of the Southern Ocean when occasionally-occurring atmospheric anomalies lead to disturbances in the circulation of water masses (Stein, Heywood 1988). Indirect data referring to successful reproduction among seals and penguins on Bird Island allow it to be presumed that in the 10 subsequent years, 2 are not typical on account of very low krill biomass (Priddle *et al.* 1988).

In recent years some observations have suggested an interdependence between the occurrence of the periodic warm current "El Niño" and variations in biological processes within Southern Ocean geoecosystems. J. Priddle *et al.* (1988) pointed out that some years characterized by low krill biomass in the region of the Scotia Sea and Bransfield Strait fall one year after "El Niño" appears. Periodic fluctuations in the abundance of Weddell, Crabeater and Leopard Seals also seem to be correlated with "El Niño's" appearance (Kock, Shimadzu 1994).

The variability of biological processes can be expressed by reference to multiyear changes in the ichthyofaunal composition of Admiralty Bay. The most-frequent fish in the shallow zone were: *Notothenia corriceps*, *Notothenia rossa*, *Goobinotothen gibberifrons*, *Lepidonotothen nudifrons* and *Trematomus newnesi* (Zadrożny 1996). In 1977, *N. rossi* was dominant over *N. corriceps*. In 1979, the abundances of both were comparable, while in autumn 1988, *N. corriceps* dominated over *N. rossi*, as again in 1994/95 (Zadrożny 1996). In Admiralty Bay, *N. rossi* did not occur at all during spring and autumn 1990, being replaced by *N. corriceps*. Observations from the region of Potter Cove immediately to the west of Admiralty Bay (Barrera-Oro, Marschoff 1990) attest to variations in the composition of the dominating fish populations in different years. F. Nast *et al.* (1988), who examined the composition of the ichthyofauna around Elephant Island, established that in 1978-81, there was a radical change in the dominance structure with *Notothenia rossi marmorata* and *Champsocephalus gunnari* being replaced by *Nothotenia gibberifrons*. The authors suspected that exceptionally high catches of *N. rossi marmorata* and *G. gunnari* around the Antarctic Peninsula in 1978–1981 could have brought about the effect. Similar data relating to variability in the ichthyofaunal composition were gathered for other areas around the Antarctic Peninsula. Thus, for example, post-larval stages of *Notothenia gibberifrons* occurred in the Bransfield Strait in exceptional abundance in 1976, while in 1981, only single individuals were caught (Kellerman, Kock 1988).

The accessibility of krill at the proper time and distance from breeding areas is decisive for the successful reproduction and hence the abundance of penguins (Trivelpiece *et al.* 1987). In years with low krill biomass high mortality among seals and penguins is noted, as krill is the main food of these species. Considerable fluctuations in their abundances are therefore observed (Priddle *et al.* 1988).

Penguin populations in Admiralty Bay vary significantly in size. In the case of *Adelie penguins* (*Pygoscelis adaliae*) on the western coast of Admiralty Bay a great decrease in numbers was observed, from about 33,000 pairs in 1980, to about 14,000 pairs in the breeding season of 1989/90. It may be added that the greatest fall in numbers occurred at the beginning of the 1980s, that is in the period of highest air temperature. The numbers of pairs of *gentoo penguins* (*Pygoscelis papua*) nesting in the area of Admiralty Bay fluctuates considerably from year to year (Myrcha 1992). This mainly happens due to atmospheric changes in the first half of October, when this species sets out to breed, as well as during incubation and egg maturation (Moczydłowski 1986). Thus, for example, in 1985, great storms destroyed all penguin eggs at the Thomas Point colony. The Chinstrap penguin *(Pygoscelis antarctica)* was most numerous in 1978/79, but in the 1989/90 season in the area of SSSI No 8 their numbers were lower by a factor of 2.5 compared to the population 10 years earlier. This variability remains difficult to explain.

In the research seasons 1988–1992 and 1994–1995, the abundances of four pinniped species in Admiralty Bay: crabeater seals, sea elephants, leopard

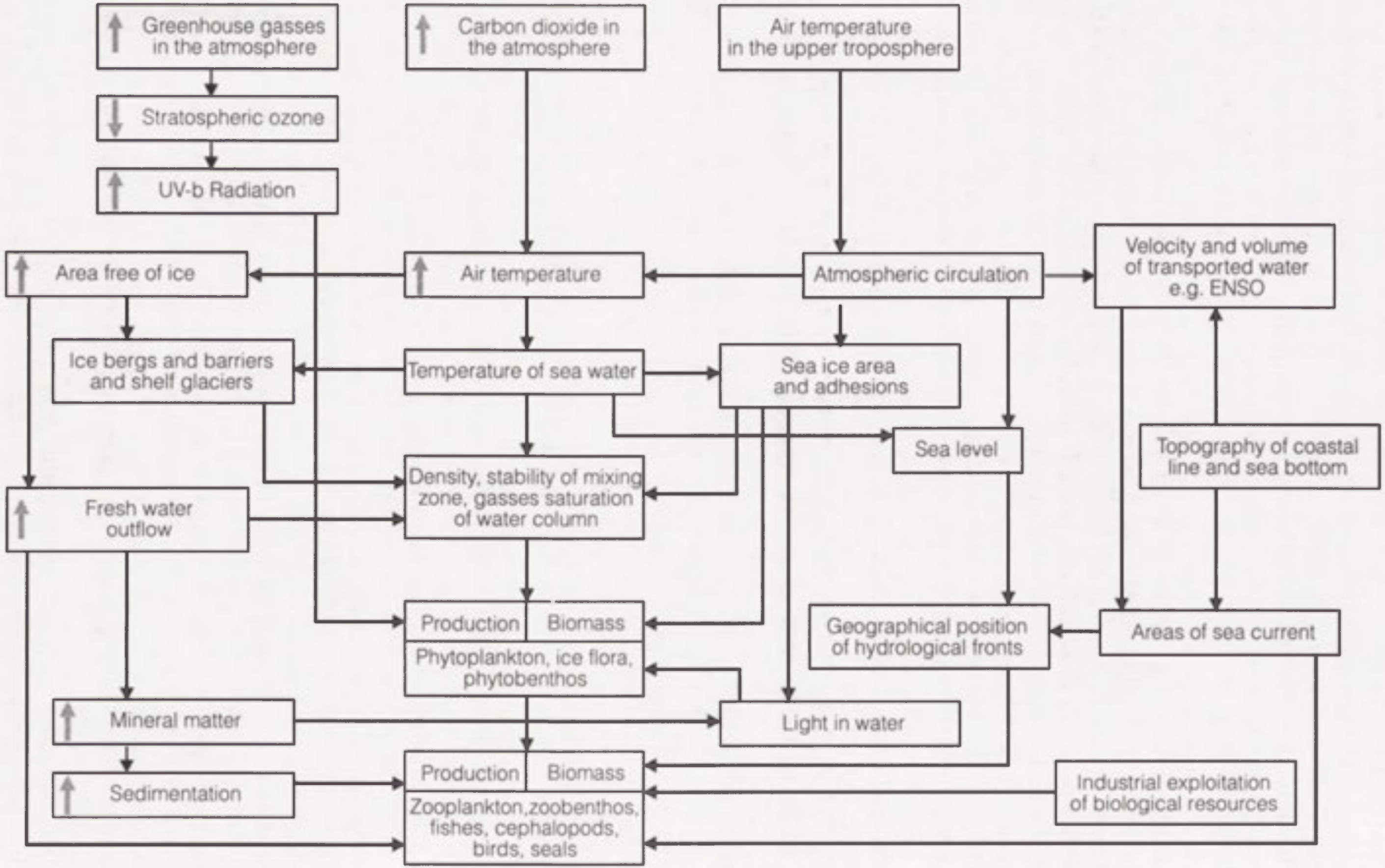

Fig. 3. Relationship between the Antarctic geoecosystem and global climatic and antropoghenic factors

seals and eared seals demonstrated no statistically significant changes (Rakusa-Suszczewski *et al.* in press). The number of sea elephants varied cyclically during the year, whereas differentiation in the populations of leopard and crabeater seals was highly irregular. The number of eared seals would change cyclically with two peaks, in autumn and winter. The observed decrease in the numbers of Weddell seals is likely the result of the development of the Ferraz and Machu-Picchu Stations, where these species existed earlier.

A particular role is played by changes caused by direct anthropogenic interference. These include a dramatic increase in the numbers of eared seals, almost annihilated by hunting in the 19th century. Over-killing of whales seems likely to have played a role as these used to be competitors for food (Kock, Shimadzu 1994). The numbers of now-protected whales is growing as well, but at a much slower rate. Less influence of anthropogenic factors is reflected in variations in the distribution of Branchinecta in seasonal water bodies close to the Arctowski station (Janiec 1991), the appearance in the station's vicinity of a *Poa sp.* grass brought there in recent years by tourists (Olech 1996), and variations in the numbers of Weddell seals as a consequence of research station development (Rakusa-Suszczewski *et al.* 1997).

To sum up the anticipated relations between changes in the Antarctic geoecosystem and operating anthropogenic factors and global climate change Fig. 3 presents a synthesis in the form of a diagram.

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