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INSTITUTE OF GEOGRAPHY AND SPATIAL ORGANIZATION

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67

GLOBAL CHANGE: POLISH PERSPECTIVES 3

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STUDY ON CHANGES AND SELF-SIMILARITY IN CLIMATE DYNAMICS OVER THE EUROPE-NORTH ATLANTIC AREA

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ABSTRACT. To the study of climatic changes in the Europe–North Atlantic region some methods classical to the meteorological community, such as an empirical orthogonal function (EOF) decomposition and analogues searching were combined with methods used by the contemporary theory of dynamical systems. In this paper we try to resolve a question about the nature of changes in the climatic system, starting from an investigation as to whether features of self-similarity typical for strange attractors (SA) remain invariant or break. The essence of our approach is a reconstruction of a coarse-grained dimension of a strange attractor on the basis of time series of meteorological data. The best results were obtained by joint application of the EOF and Takens methods with a local approximation of a strange attractor trajectory by the fixed mass (analogue) method. The presented method has value not only as a research tool and has since October 1944 been implemented operationally at IMWM (Poland) to forecast a half-year air temperature anomaly within the mid-latitude belt.

KEY WORDS: climate modelling, climate change, chaotic strange attractor, empirical long-term forecasting.

INTRODUCTION

The article consists of four parts. The first part of the paper describes methods applied to the investigation of climate change, with special attention to the theory of dynamical systems. The second part describes the air temperature data used and the standard empirical orthogonal function analysis accomplished. In the third part a dimension of a real-world climatic strange attractor is estimated using the mentioned data. As a result, a "statistical" (coarse-grained) dimension of SA was obtained. In the fourth part, taking into consideration an evaluated dimension of the SA, the method of analogues well-known in meteorology is developed and applied to long-term forecasts of an air temperature field over the considered area.

A large number of investigations on climate change driven by the supposition of an increased greenhouse effect show that the reaction of the climatic system to external forcing is very complex and susceptible to various interpretations. On the basis of an analysis of various meteorological data the majority of researchers are coming to the conclusion there is a case of global warming at present. However, the existing empirical estimations of climate changes in different temporal and spatial scales are unbalanced, and sometimes directly opposite to each other in that which concerns the character of the change (monotonic, floating or jumplike heating), the time of its coming and duration. In our opinion this is caused not only by the complexity of the event and the excessively short time series used for a study of the problem, but also by a lack of adequacy of the mathematical apparatus applied.

The traditional way for climate change investigations on the basis of observations is the application of correlation and a spectral analysis. Recently R. Sneyers (1992) has given a critical review of these means of analysis. He and others described many developments of these approaches, but such methods could be applied to stationary time series only. In our opinion, some progress in such investigations could be achieved by rejection of the principle of stationarity. As a basis for this we used the contemporary theory of dynamical systems with chaotic behaviour, introduced for the first time to meteorology by E.N. Lorenz (1969). At present his theory has quite wide applications in studies of atmospheric circulation (Sonechkin 1984, Ghil 1987, Fraedrich 1987).

According to the theory of dynamic systems, the dynamics of the weather may be adequately modelled by the system of differential equations which describes the hydrodynamics of the atmosphere (or, if we wish to consider much longer time scales, by the appropriate system of equations for the atmosphere and the ocean coupled and dynamically interactive). In such a system, steady motions (i.e. those considered after a sufficiently long time period of integration without a change of external forcing) create a specific set in a phase space of the climate system. The complex (fractal) geometry of that set and the instability (chaoticity) of all the inherent movements gives it the name of strange chaotic attractor (SA).

The SA phenomenon creates the basis for the theory of predictability of the numerical, hydrodynamical long-range weather forecasting developed by E.N. Lorenz (1963, 1969, 1982). It seems quite paradoxical that the same phenomenon permits us to give reasoning for the principal predictability of the climate. Details of our hypothesis will be published in another paper, but at this stage the attempt is made to formulate a basic principle of suitable proof.

It is a well-known fact that every SA has an invariant (stationary) probability distribution (IPD), according with some fixed (in the above defined sense) motion of a dynamical system of interest observed more or less frequently. Exactly speaking, many or even infinitely many IPDs exist on every SA. For example there are IPDs concentrated onto any of the periodic movements belonging to the SA. But there exists a special IPD the support of which is the all attractor set. It is natural to term it a climatic distribution of probability (CDP) or simply a climate. CDP, which can be prescribed in any fixed moment of time is stable in that sense, then as time passes, any probability distribution (appart from the singular IPD listed earlier) approaches CDP. For example, a prescribed initial probability distribution can imitate uncertainty of our knowledge about the initial stage of the climatic system during the weather forecast. The spread of that probability distribution in time and its approach to the CDP describes a process of losing the predictability. The stability of the CDP means that generally it may be extrapolated to the future more accurately, as the period of extrapolation will be longer. In that manner, although the temporary stage of the climatic system (the weather), is in principle unpredictable for a long-range period due to instabilities of individual movements of SA, the longtime behavior of the weather (climate) is, due to the stability of the climatic strange attractor as a whole set and its CDP stability, predictable the more accurate as the longer is the period of its forecast.

It needs to be said that the last sentence is valid only when the external forcing of the climatic system is constant and known. In that case, in principle, the system of equations describing the evolution of the climatic system allows us to write the system of equations for the evolution of any PD for that system. According to the theory of dynamical systems, if an external forcing is constant then the system will always have the simple attractor — a steady point in the phase space of all possible probability distributions. That steady point corresponds to the CPD. Motions in the phase space of the probability distribution are attracted by that steady point from any initial distributions.

Such a situation really becomes complicated if the external forcing of the climatic system is not a constant one. For example, if we do not include the ocean into the climatic system and do not parameterize the annual course of solar insolation, then the latter, even being strongly periodic, can initialize (see, for example the paper of N.M. Datsenko and N.N Sonechkin, 1992) subharmonic (with a period of two, three or more years) and even chaotic motions in the climatic system. In such a case CPD does not have to be invariant, but will change over time. In such circumstances the limit of climate predictability could be created in a manner similar to the limit of weather predictability, but, of course, placed much farther along the time axis.

Since CPD is not observed directly and can only be estimated as a moving average on the basis of a sufficiently long time series of meteorological observations, it is important to distinguish between inherent (natural) climate variability as a variability of its current CPD from long-term changes in weather regimes. This latter can be observed during the implementation of any realistic movements into the climatic real-world "attractor" (which remains invariant as a set), having a small probability of appearance according to CPD. With that, long-term and significant weather anomalies will be explained not as a modification of external forcing for the climatic system but as pure internal features of the climate as a chaotic and dynamic system. It is easy to imagine a mixed case, when a change of SA as a set leads to a growing probability of observation for some specific motions which were possible (but of low probability) in changed climatic conditions also.

DATA FOR CLIMATE DESCRIPTION

For the description of the climate in the Europe–North Atlantic region, monthly mean air temperature data from 1851 to 1993 from 55 meteorological stations were used. One part of this dataset was prepared in Moscow, in the Laboratory of Stochastic-dynamical Methods of the Hydrometeorological Research Centre of Russia, another part was prepared in the Long-Range Meteorological Forecasts Department of the Institute of Meteorology and Water Management (Warsaw, Poland) and a third part was taken from the CDIAC data base (Jones 1985). Computed for each station were mean air temperatures for the warm (IV–IX) and cold (X–III) half-year periods of every year in the archive. The long-term means using a 143-year time series were computed for both periods. After computing the variate (deviation from the climatic mean) the joint covariation matrix (the same for both periods) was constructed. It is worthy of note that covariation matrices, evaluated for each half-year season separately are quite different at first glance, but they have practically the same systems of eigenvectors (empirical orthogonal functions — EOF). All differences between matrices are contained in differences between their eigenvalues. For this reason we used only one eigenvector system for both seasons.

Figures 1–3 show the first six vectors of the described system. Almost all components of the first EOF have a negative sign (apart from two stations in Greenland), while all other EOFs have varying signs. Therefore the first expansion coefficient of the half-year mean air temperature anomaly field for the cold period should be used for an estimation of the "coldness" or "warmness" of a period over the whole area. Looking at the time series of 143 values for the first expansion coefficient we could make judgements about general cooling or warming of the climate in the considered region. The time series of next expansion coefficients of EOF are already useless for an estimation of the climatic trend, but they include suitable information about the evolution of climate variability and the distribution of locally warmer or colder places in the considered region. The second EOF (Fig. 1b) describes temperature anomalies of different sign over western and eastern parts of the area. The third EOF (Fig. 2a) describes similarly large areas of anomalies but extended in a north-south direction. With some degree of conventionality we can consider these two EOFs a complex pair obtained one from another

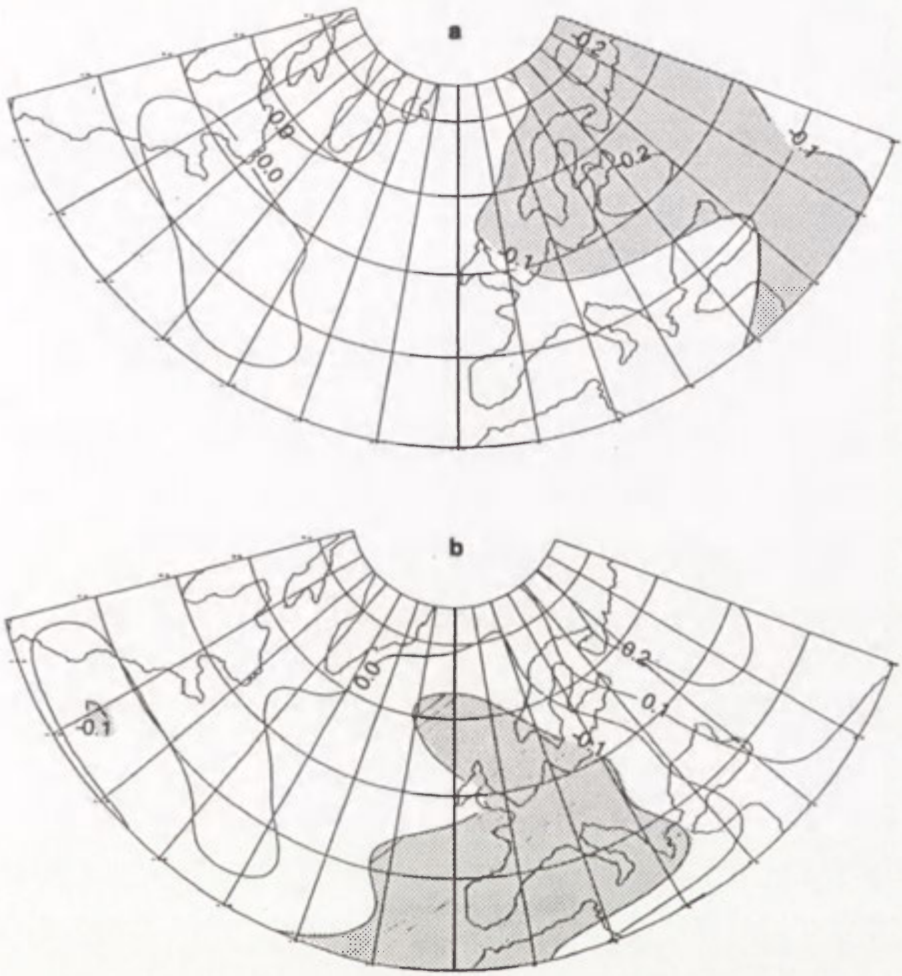

Fig. 1. First (a) and second (b) eigenvalues of half-year mean air temperature anomalies

through rotation of a field by 90°. The first eigenvalue, which, as noted earlier, describes the general trend in a temperature field, is about 2.5 times greater than the second and 3.2 times greater than the third. The second and third eigenvectors describe the centers of the largest temperature anomalies in the considered region. The joint contribution from the second to fifth eigenvectors is very close to the magnitude of the first eigenvalue. Interesting features are observed if we estimate the dispersion of the second and third EOF coefficients for warm and cold periods separately. The dispersion of a second EOF for the warm half year period is almost twice as great as the dispersion for the cold period. As a result, during the warm half-year period the change of sign of the temperature anomaly more fre-

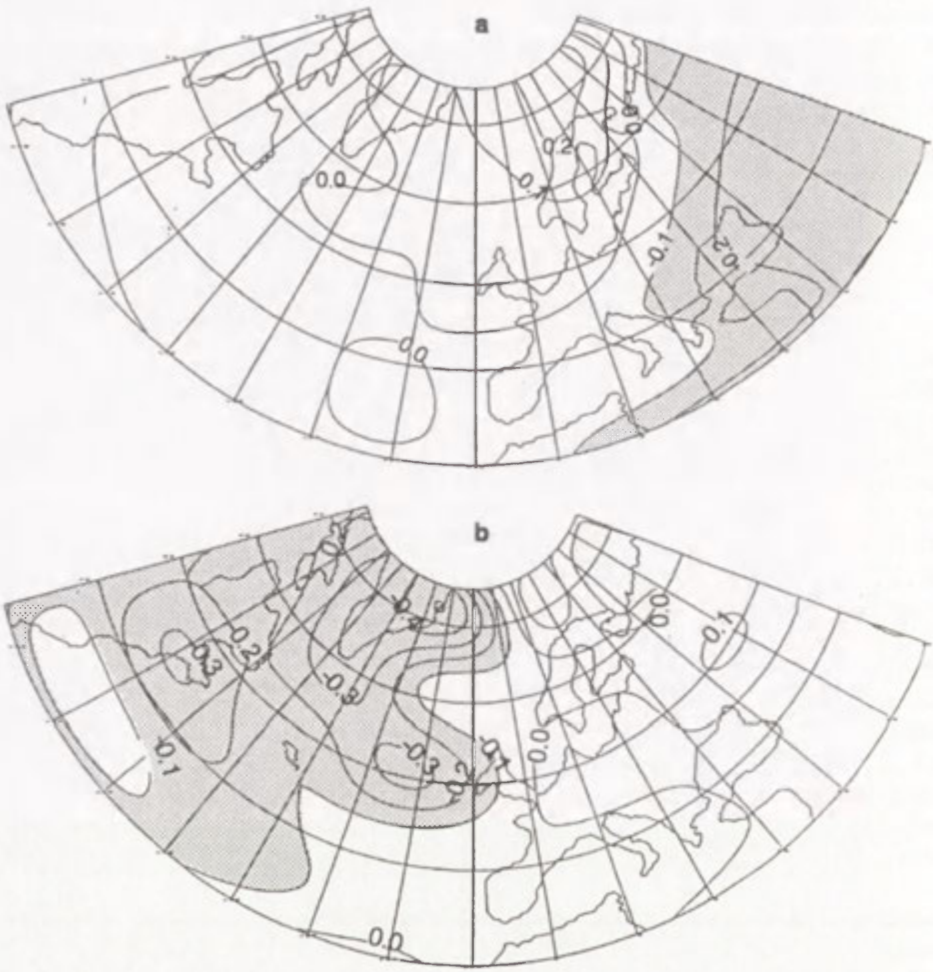

Fig. 2. Third (a) and fourth (b) eigenvalues of half-year mean air temperature anomalies

quently occurred in the west–east direction. A similar, but weaker effect is observed during the cold period. Finally during the year as a whole a west–east variation dominates.

Looking at the fifth EOF (Fig. 3a) we can see the quite large centre of a temperature anomaly over Central Europe. This means that this EOF in particular is most important for a description of half-year temperature anomalies over Poland. The fifth eigenvalue is about four times lower than the second one, but about twice as great as the 6-th one. The first five eigenvalues are responsible for more than 73% of the common dispersion of the temperature anomaly field and the first ten eigenvalues for about 85% (Table 1). In general, the higher EOFs show very complex patterns, difficult for reasonable

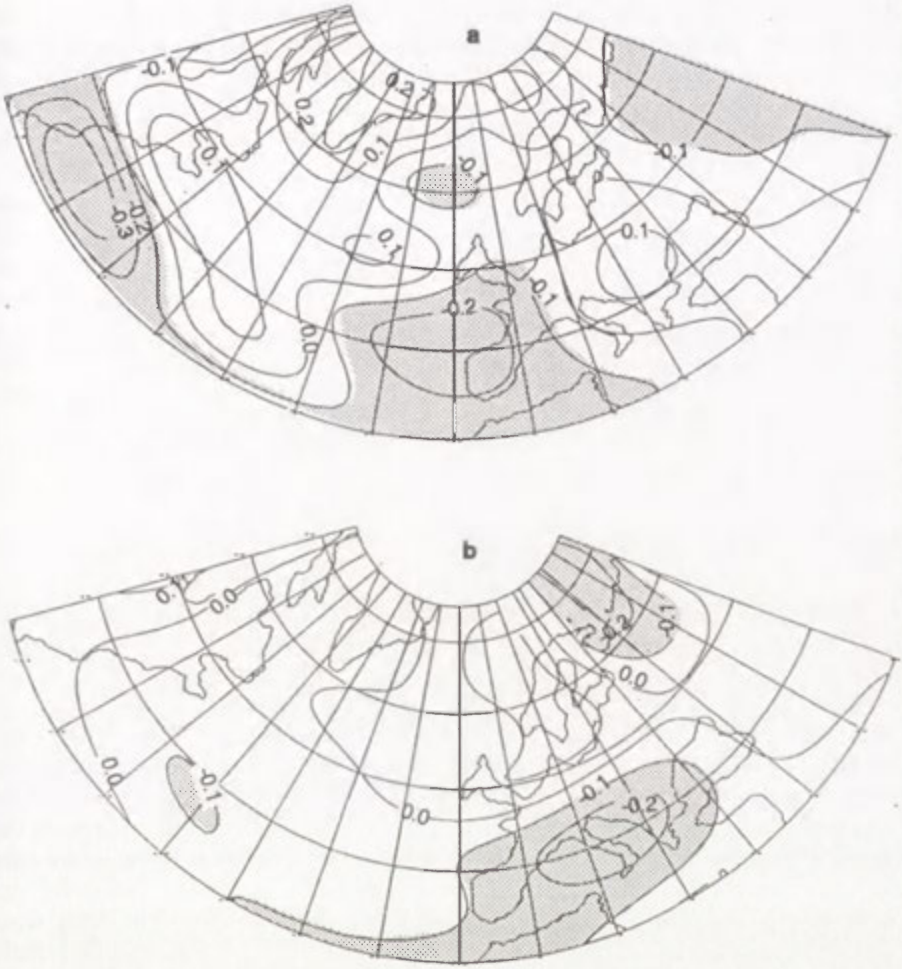

Fig. 3. Fifth (a) and sixth (b) eigenvalues of half-year mean air temperature anomalies

physical interpretation. It seems that their forms are to a great degree determined not so much because of real fluctuations in the temperature field, but because of errors in meteorological observations and a certain nonrepre sentativity of individual data stations, which, as a consequence of the independence of air temperature measurements at different stations should be uncorrelated in space. Therefore we could take as a first estimation of the upper limit of the noise level in the considered data a magnitude of the eigenvalue of about 1.0. More detailed consideration shows that the value of the 11th and next eigenvalues are not noticeably different. The smallest has an order $2*10^{-2}$. This means that the level 1.0 is not a level of a noise "plateau" and that EOFs of the second and even few next decades do not represent a pure noise. It may therefore be that we cannot exclude their consideration during the analysis of climate dynamics. However, as will be shown in the next section, these fears are superfluous and the analysis of the dynamics of contemporary climate changes may be limited here to the first ten EOFs only.

TABLE 1. First ten eigenvalues and correspondent percentage of the total dispersion (PTD)

No	Eigenvalue	PTD
1	25.108	36.3
2	9.595	50.1
3	7.868	61.5
4	5.283	69.1
5	2.633	72.9
6	2.141	76.0
7	1.897	78.8
8	1.703	81.2
9	1.468	83.3
10	1.304	85.2

ESTIMATION OF THE DIMENSION OF THE REAL-WORLD CLIMATIC ATTRACTOR

For a more realistic estimation of the number of eigenvectors which need to be taken into consideration during investigations of climate dynamics over northern hemisphere mid-latitudes, estimates can be made of a dimension for a climatic strange attractor which forms a mathematical model of our dynamical system. During the last ten years the most frequently used method for the reconstruction of a state vector on the basis of a time series for one meteorological variable was the method of F. Takens (1981). The first work of this kind applied in meteorology was the paper of C. Nicolis and G. Nicolis (1987) based on the P. Grassberger and I. Procaccia (1983) method of the fixed radius. Later on, other articles, such as papers by K. Fraedrich (1987), A. Hence (1987), C.T. Essex et al. (1987), B. Saltzman (1988), A.A Tsonis and J.B. Elsner (1989), K. Fortuniak (1994) also used the P. Grassberger, I. Procaccia method. These works showed some complications which are characteristic for the procedure of estimation of the dimension of a climatic SA using relatively short time series. The paper of P. Grassberger (1986) was the first that critically pointed out the possibilities of estimating the dimension of the climatic attractor. From among many articles, the papers of T.R. Kriszna-Mohan et al. (1989), L.A. Smith (1988) and L.A. Smith et al. (1986) are of significance for the development of a method of estimating the dimension of the attractor and, what is more important, for interpreting these computations. The papers of A.A. Vinogradskaja et al. (1990) and K Fraedrich and R. Wang (1993) showed that joint application of the empirical orthogonal functions method together with the method of Takens is more efficient for reconstruction of the vector state of the climatic system. The papers of R. Vautard and M. Ghil (1989) and N.E. Zimin and D.M. Sonechkin (1992) formulated the idea that the chaos observed in the climatic system has a space-time feature. Similar information was presented by E.N. Lorenz (1982). Such a complex structure for an attractor cannot be placed in some small dimension, as supposed earlier. But a joint feedback of processes in different parts of the climatic system could be so complicated and indirect that in many cases some interactions could be omitted to artifically decrease the number of degrees of freedom of the climatic system. This means, that for the analysis of that or another climatic process it is possible to use the model of a strange attractor with the relatively small dimension. On the other hand, trying to rebuild the model of the climatic system on the basis of real meteorological fields with a prescribed level of noise we are forced to apply only large-scale features of climate dynamics. Under these conditions during our computations only "coarse-grained" (Zimin and Sonechkin 1992) or "statistical" (Vautard and Ghil 1989) dimensions of the attractor can be estimated. The dimension is smaller the shorter the length of the time series considered, while the level of noise in observations is larger. Experiences from the last two papers and theoretical investigations concerning the analysis of singularities show, that as a first approximation of the climatic real-world attractor we can take the number of these EOFs, whose eigenvalues are sufficiently greater than the level of the noise plateau in observed data. However, the well-defined plateau in our data is difficult to fix, which forced us to direct computations of a coarse-grained dimension for the climatic attractor. Taking into consideration the fact that, even for such very general features of temperature anomalies as estimation of their sign, the length of series of the order 2^D (where D is the expected dimension of the climatic attractor) is needed, we come to the conclusion that the method of Grassberger-Procaccia, which assumes smooth changes in the magnitude of the radius of the space surrounding a prescribed point in a phase is of little use. Less sensitive to the short length of the observed time series is another method, well-known in the theory of dynamical systems as the method of fixed mass or the k-th nearest neighbour (Badii and Politi 1984). This method was applied in the works of D.M. Sonechkin (1988) and A.A. Tsonis and J.B. Elsner (1989) and its practical implementation was described in the paper by D.M. Sonechkin et al (1995).

The method of the k-th nearest neighbour is as follows. Let x(t), t = 1,2...T consist of a time series of state vectors of the climatic system constructed in our case from d (d = 1,2,...55) first expansion coefficients of EOF for both periods (half-years) so that the dimension of a vector state (following Takens, the dimension of an embedded space) is equal to 2d. We choose from this series, in accordance with a climatic probability distribution of the vector state, Nr reference vectors $x(t_r)$ (Nr < T) and for each of them, according to a chosen measure of similarity (analogy) we find the first, second, ... k-th nearest neighbour in the phase space, or, as meteorologists say, we find its k analogues. If the investigated series was constructed from a chaotic dynamic system, then the averaged distance for all groups of vectors $r^{Nr}k$, 2d should follow the principle of scaling

$$r_k^{Nr}{}_{2d} = C \cdot k^{1/D(2d)} \tag{1}$$

where c is weakly dependent on or totally independent of k.

$$D = \lim_{\substack{T \to \infty \\ 2d \to \infty \\ 2d/T \to 0}} D\,(2d) \tag{2}$$

In reality the attainment of the limiting point is impossible, and we need to consider only some number of nearest neighbours (analogues) from a finite set. From the theory it is known that scaling is the most sensitive to noise in the first analogue. For this reason we used $k > 1$ for estimation of the dimension D. The limited length of the time series does not give us a possibility to choose a quite large k. Practically, we found that the number of considered analogues could not be higher than 10–20% of the total number of vectors. Similarily to in the Grassberger–Procaccia method, a value of D is estimated from a succesively increased dimension of embedding (2d).

In Figure 4a dependency (1) is presented on a logarithmic scale for k= 1–10 for each year of the decade 1983–1992 under the condition that the choice of analogues is made from preceeding years, starting from year 1851. The value of 2d is equal to 2*10, i.e. for the reconstruction of the state vector of the climatic system we used the first ten coefficients of EOF for each half-year period. It is evident that even values of logarithms of distances to the k-th neighbour are sufficiently variable from year to year, and their variability from one value to another is also quite large, so all lines have a concurrent mean slope and their distances on the vertical axis are quite large. This means that good analogues exist for some years but not for others. Lines will be more close to each other after renorming distances to the k-th analogue by a suitable distance to the best antianalogue (antilog). This approach takes into consideration the non-homogeneity of the climatic real-world SA (see Fig. 4b). The process of averaging through all the years for the recent and remaining decades of the 19th and 20th century starting from the decade (1963–1882) smooths yet more of these differences and gives the scaling (1) for considered series more evident. Examples of such averaged graphs for the last two decades are shown in Figure 5. They give a more accurate estimation of D(2d). The simplest form of such an evaluation as a function not only of 2d but also of k could be given through comparison logarithms of distances to the kth and (k+1)th neighbour.

$$D(2d,k) = \frac{\ln(\;+1) - \ln(k)}{\ln r_{k+1,2d} - \ln r_{k,2d}} \tag{3}$$

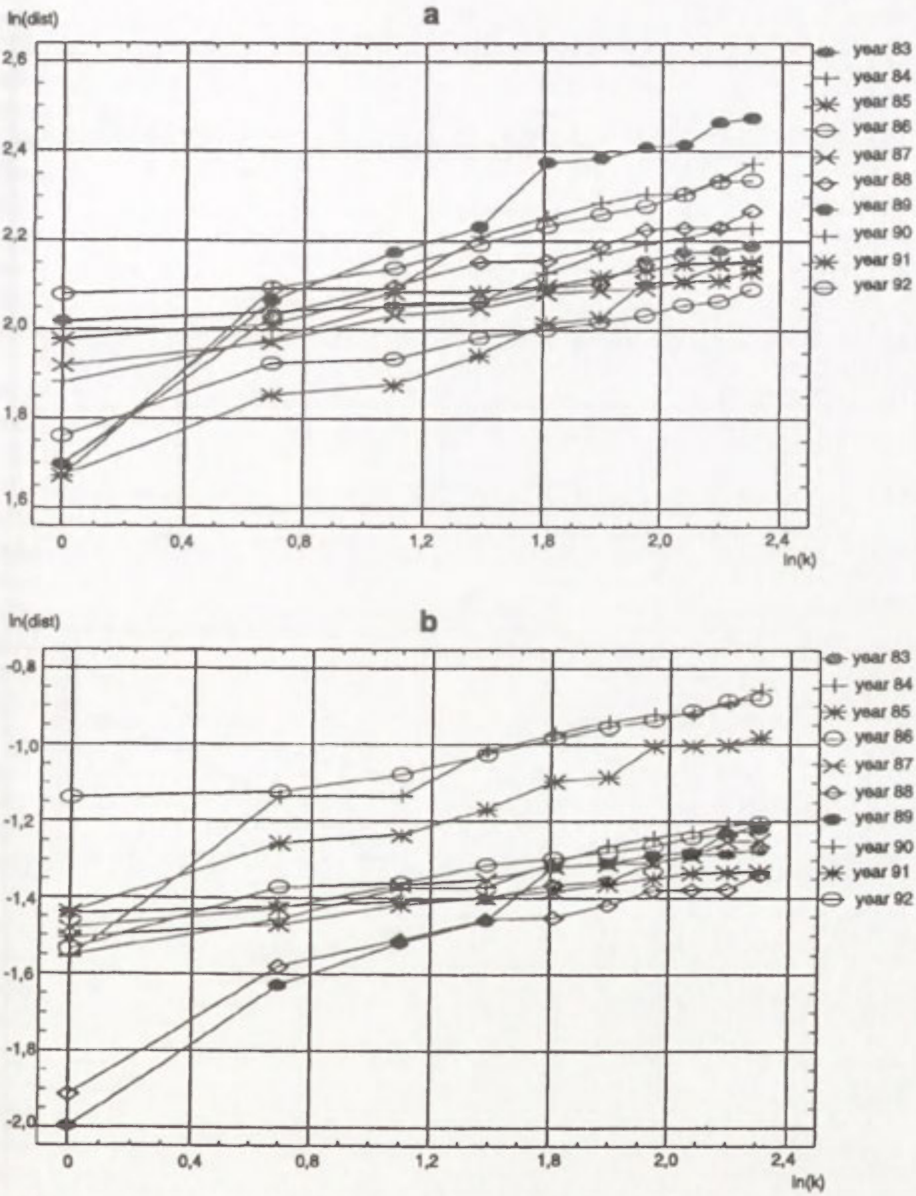

Fig. 4. Log-log plots of distance to the analogue state as a function of neighbour number (a) without normalization (b) with antilog normalization

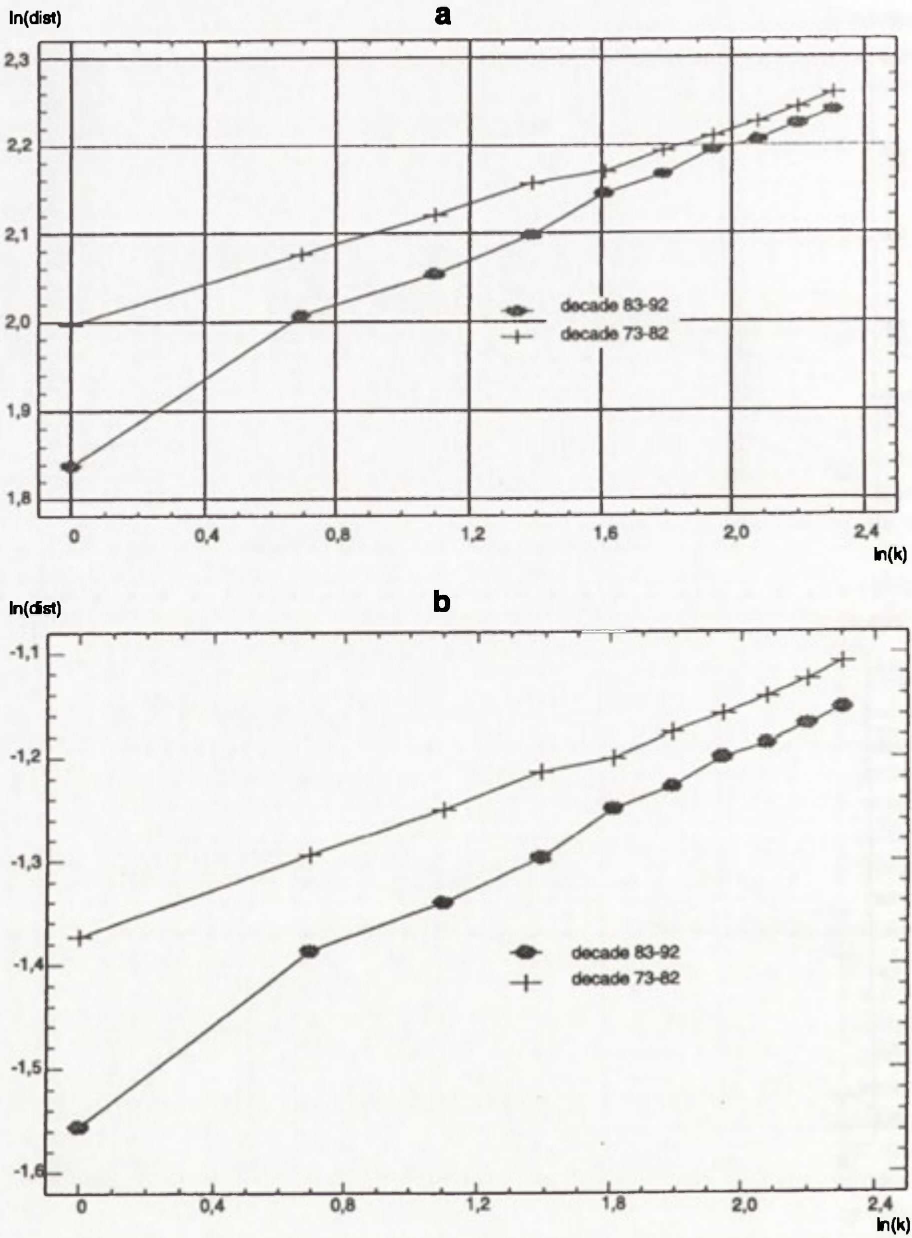

Fig. 5. Dependence of distance from neighbour number for two selected decades (a) without any normalization, (b) with antilog normalization

with the assumption that the value of lnC is independent of k. The last behaviour is observed only for SA being a simple fractal set, but such a situation is absolutely unrealistic. Practically all fractals observed in nature consist of more complex objects and their scaling properties vary from one part of an object to the another. Such objects are usually called inhomogeneous fractals or multifractals. They have as minimum a logarithmic dependency of values C from K, and as a result scaling (1) demonstrates an oscillatory component (see for example articles of R. Badii, A. Politi 1984, and L.A. Smith et al. 1986). Estimation (3) is changed with k. Examples of estimation (3) for $k = 1 \div 9$ averaged for all the considered series of observations are presented in Fig. 6 for different values of 2d from d = 1 to d = 55.

It could be seen that estimation (3) varies a little for a small dimension of embedding 2d (to d equal ten) for all ranges of values used, with the sole exclusion of k = 1, where it is in all cases too low. At 2d equal to or greater than 40 estimation (3) is sufficiently more oscillating and more dependent on k, which is most likely a consequence of too short a length of series. For this reason it is undesirable to use such large dimensions of embedding, which means that "coarse-grained" estimation of the climatic real-world SA dimension should be no more than 10 in the considered case (according to the theory, the relationship between the dimensions of the attractor and the space of embedding should be as $2d \geq 2D + 1$). From graphs on Fig. 6 it is evident that with an increase of 2d an estimation D according to (3) also increases (on average). Discarding value k = 1 as a truly too low outlier we could calculate a root mean square estimation of dimension D(2d) from relation (1) for all remaining values of k up to k = 10. This dependency is shown in Fig. 7. For comparison, the eigenvalues of our covariational matrix are also included in Fig. 7. The dependency of D on 2d approaches a horizontal asymptote close to 10 as 2d increases. This value could be taken as the upper limit in our estimation of the dimension of the climatic real-world attractor. The most intense increase of the function is observed for $2d \leq 2*10$ or even for $2d < 2*5$, where at the same time the most intense decrease in the eigenvalues of the covariational matrix is observed. Though a full saturation of a graph, i.e. achievement of a horizontal asymptote is not gained, as a "plateau" in eigenvalues is not present, it seems reasonable to estimate a "coarse-grained" dimension of SA from the value suited to the most distinct break in both graphs as D = 10. Future investigations of climate dynamics will be confined to a consideration of the first ten EOF coefficients for both hemispheres only, i.e. we limit ourselves to the twenty-dimensional space of climatic system states.

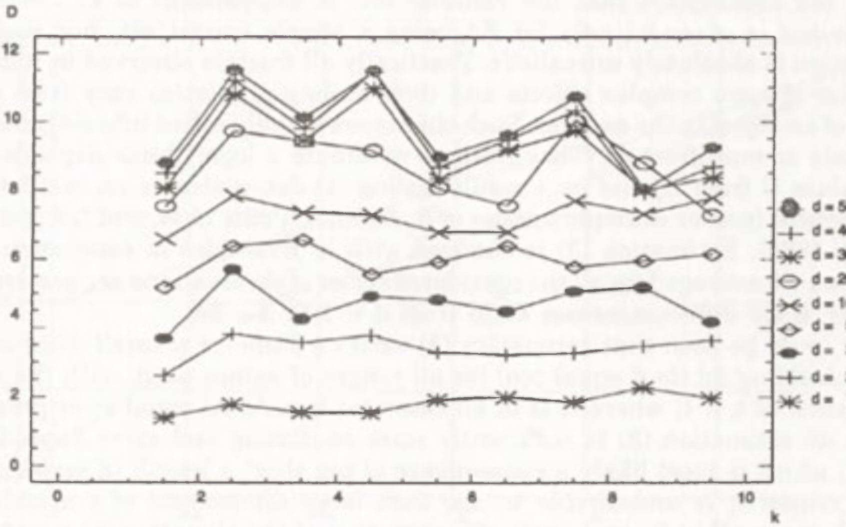

Fig. 6. Mean SA dimension as a function of 2d and k

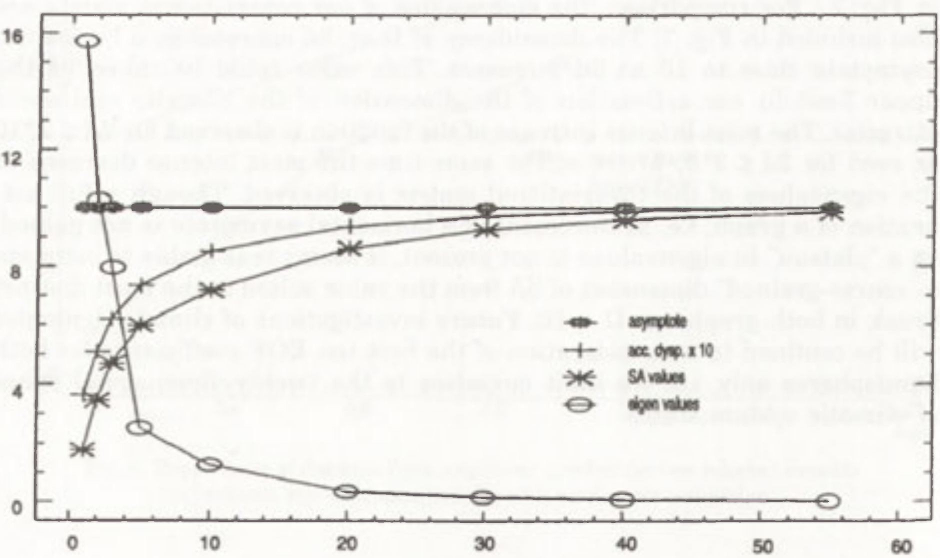

Fig. 7. Mean square estimation of SA dimension

FORECASTING A HALF-YEAR MEAN TEMPERATURE ANOMALY FIELD USING CLIMATOLOGICAL ANALOGUES

With the exception of the limited success of the hydrodynamical modelling of the global circulation of the atmosphere, numerical long-range weather forecasting remains an unsolved problem. In most meteorological services simple empirical (mainly statistical) approaches connected to the duty forecaster's insight are applied for practical long-range forecasting. Among these approaches a large place is occupied by "the analogy" method, for example the work of R.E. Livezey and A.G. Barnston (1988). In that method it is assumed that the similarity of an actual state of a climatic system to some state-analogue observed in the past should be maintained for some time in the future. Therefore as a forecast we could choose this analogous state from the past, which was observed as next to the analogue of the recent state. During realization of an analogue method questions about the choice of features of the climatic system and a description on their basis of the principle of analogy arise. Taken's method shows, that generally any features of the climatic system observed for a sufficiently long period and with comparatively good quality could be used to search for an analogue state, and it is appropriate to make their number equal to the dimension of the climatic SA (more precisely, the dimension of a state space of the climatic system should be taken to be equal to 2D + 1). As a measure of the analogy we could take an ordinary euclidean or other similar distance. For example, a distance defined as a maximum difference of compared values of any considered features could also be a measure of an analogy. In exemplifying simple dynamical systems many articles (Farmer and Sidorovitch 1987, Sugihara and May 1990, Broomhead and King 1986, Smith 1992) have shown that the method of analogues really works better than other schemes of statistical forecast (for example a linear regression), but needs sufficiently representative time series of past states of the considered dynamical system. Insufficient length of a series and a high level of noise in historical data could totally detract from the method of analogues, after all as the all statistical methods.

The meteorological literature now contains a few different examples of the application of the analogy method to the forecast of the behaviour of chaotic dynamical systems. All of these could be divided into two large classes, connected to:

— the global approximation of SA,

— the local approximation of SA.

The method of global approximation of climatic SA for a long-range, analogue forecast is described in detail in a paper by A.A. Vinogradskaja et al (1990), which is the first work concerning the meteorological application of the mentioned approach.

According to the estimation of the dimension of the climatic attractor the sequence x(t), t=1,..T of state vectors is formed, which will be used for the selection of analogues to the actual state $x(t_0)$. Though the climatic SA is, generally speaking, a fractal set, we suppose that its "coarse-grained" description forms a smooth manifold of dimension D, given by the series x(t), t = 1..T in a space of states of the climatic system. An actual SA is likely to be imposed on this manifold as a skeleton. We will approximate only a manifold, representing each known component of a series x(t) by expansion with regard to the system of some basic functions

$$x(t) = \sum_{i=1}^{\infty} x_i(t)\,\varphi_i \tag{4}$$

practically limiting the number of components of the series to M. For example, norming preliminary vectors x(t) in such a way that all of them are placed into a unit hypercube, we could take as a basic trigonometric functions as the expansion basis.

$$\prod_{i=1}^{M} \cos(2\pi k x_i),\ i = 1 \div M,\ k \in Z^+$$

Since the dimension of the manifold is lower than the dimension of the state space, there should exist between coefficients of expansion (4) some dependencies of the type

$$x_k(t) = f(x_j(t)),\ j = 1 \div m1,\ k = m1 \div M \tag{5}$$

Relation (4) represents a general description of a manifold with dimension D embedded in a space of dimension 2d + 1. The constructive description of formula (5) needs the definition of a type of a function and the estimation of its parameters in a manner optimal to the existing historical data. In the simplest case we could take this function to be linear

$$x_k(t) = \sum_{j=1}^{m1} a_{kj} x_j(t) \tag{6}$$

or in the vectoral form

$$y = Xa \tag{6a}$$

and to prepare for our data X(t), t = 1,T the system of normal equations of type (6), whose solution could be estimated by the least squares method. In reality quantities m1, M and T are values of the same order of magnitude. Therefore, the system of normal equations is ill-conditioned. For the stabilization of its solution we need to use any additional information, i.e. we need to perform the regularization of the least squares solution. Many methods for this exist. For example in A.A. Vinogradskaja et al. (1990), during the inversion of the system (6a) the procedure was to be formal, by fitting the parameter of regularization α to the historical data:

$$a = (x'x + \alpha I)^{-1} x'y \tag{6b}$$

where I is an unitary matrix.

In many papers, more sophisticated methods are proposed, for example a method in which a direct problem conserves some invariants of a considered dynamical system. Among the invariants could be: the entropy of a system and values of its Lapunov exponents, the probability distribution of a vector y (climatic probability distribution for the forecasted parameters) and others. It leads to a problem of least squares with additional constraints of an inequality type, with well-known methods of solution.

Determining in that or another way coefficients of approximated relation (6) and choosing components j and k of a vector x(t) in such a way that j describes an actual state of the atmosphere and k describes a future state (forecast) we are able to compute values of k components and to use (4) to predict the expected state of the climatic system.

In particular realization of this scheme of forecast, taking into consideration the quite high level of noise in the temperature data and the largest sensitivity to these noises of the coefficients of EOF which correspond to small eigenvalues, we confine ourselves to the first D/2 coefficients of the EOF for each half-year and we forecast only D/2 first coefficients of the EOF for the one next half-year period. In that way the state vector x(t) is composed from three consecutive half-year periods.

As could be seen, the method of forecast which implements the "global" approximation of a climatic attractor is in essence a special example of construction of a nonlinear regression equation, where nonlinearity is taken into account through the form of basic functions (transition to the decomposition relative to this basis gives the formally linear regression equation) and the number of free parameters of the regression equation depends on the "coarse-grained" dimension of the climatic attractor. Experiences with the application of the global approximation to long-range forecasts of air temperature anomalies showed that though forecasts are informative in the sense that they are better than climate or persistance, they are too smooth, i.e. values of forecasted anomalies are usually small (lower than values of mean squared variability of the forecasted field). Tests to increase the amplitude of forecasted anomalies under the condition that dispersion of forecasted coefficients should be equal to the correspondent eigenvalue gave a remarkable increase in the root mean square forecast error. Therefore in place of a global approximation it was practically appropriate to use a local approximation of the climatic SA by means of a smooth manifold.

The local approximation is constructed using the same principle as the global approximation, but the relationship (5) is valid only for comparatively small parts of SA separately. The group of analogues is fitted to the actual state x(to) (Farmer, Sidorovitch 1987 shows that in the majority of cases a forecast based on one single analogue is worse than a forecast which used a group of analogues) and next, from that group of analogues, coefficients for relation (5) are estimated. It is assumed that due to the small area of its existence, the relation (5) is linear. Therefore, it is possible to quit decomposition of (4) and to apply components of vector x(t) directly to (5) and (6). Coefficients (6) could be computed in some way each time from the beginning or they could be estimated optionally through a minimization of mean forecast error (with or without additional constraints) using all historical data.

The best forecasts were found when a group of (D + 1) analogues was used. This number of analogues gives us a chance to gain such a distribution of analogues in a space of states that they form a convex group of points around the actual state. In that case a forecast geometrically consists of a linear interpolation in the space of states. In the opposite case a forecast is made by an extrapolation in the space of states which does not give much hope for success.

The most essential difficulty with the local approximation applied to long-range forecasting is the small volume of the meteorological archive. As a consequence the fitted analogues are not similar enough to the actual state of the climatic system. Beside this, the principle of analogy (after a similar state there should also be a similar state) could cease to work (after an insufficiently similar state there usually exists a wholly dissimilar state) and the priori linear relation (4) emerges as intolerable. Numerous experiences of duty forecasters have shown that variations in future states followed after fitted analogues to the actual state are comparable to climate variability. As a result a forecast constructed as the average of these future states is practically equal to the mean climatic state and the probabilistic forecast recommended by some meteorologists (see for example the works of Gruza 1983) is also indistinguishable from the corresponding climatic probability distribution.

Experiments carried out by us show that differences computed for each component between an actual state of the atmosphere $x(t_o)$ and each of the analogue-states $x(t_a)$

$$\Delta x_i(t_o) = x_i(t_o) - x_i(t_a) \tag{7}$$

and correspondent differences after one time step

$$\Delta x_i(t_o + \Delta t) = x_i(t_o + \Delta t) - x_i(t_a + \Delta t) \tag{8}$$

demonstrate quite strong correlation. This is true only for a small number (in our experiments for three) first coefficients of EOF and gives a remarkable increase in forecast informativity.

For this reason it seems appropriate to use the following corrective procedure for forecast by analogues. A group of about D + 1 analogues, possibly consisting of a convex neighbourhood in a space of states are fitted to the actual state. Next, differences between actual and fitted states are computed for each component. These differences are added to the corresponding states appearing after analogue states. Averaging resulting vectors in some way (uniformly or weighted inversely proportionally to initial differences) we obtained a forecasted state of the climatic system. We call that method of forecasting by analogues the linear corrective method.

Another method of correction involves the direct solving of the system of equations

$$\Delta x_i(t_{a1} + \Delta t) = A_{ij} * \Delta x_j(t_{a2}) \tag{9}$$

where $\Delta x_i(t_{a1}) = x_i(t_{a1}) - x_j(t_{a2})$ are differences between each pair of analogues. This system depicts in a linear sense the spread of chosen analogues with time. Then the problem

$$\Delta x_o(t_o + \Delta t) = A_{oj} * \Delta x_j(t_{a2}) \quad (10)$$

must be solved for every j value and the solution with a minimal norm $|\Delta x_o(t_o + \Delta t)|$ should be chosen in order to correct the forecast by analogues. We call this method of forecasting the minimal norm method.

This method of forecast was the best for prediction of the 1-, 2-, 3- and 6-monthly means of air temperature fields for the former Soviet Union. Especially valuable is the fact that the described method is able to predict considerably large values of temperature anomalies. The presented work implements the method for the Europe-North Atlantic area. We carry out experiments with practical prediction of half-year mean air temperature anomalies over Poland. In figures 8–10 examples of air temperature anomaly fields forecasted by the different schemes are presented. A short description of the main features of them is given below.

Observed (Fig. 10b): Positive anomalies with centres about +0.4°C placed over Scandinavia and the Barents Sea cover the whole of Europe with the exception of the Mediterranean region. Over Poland the anomaly has a zonal shape, from a value of 0.3°C in the north of the country to 0.1°C in the south.

Forecast as linear correction with the best analog (Fig. 8a): Positive anomalies cover the whole of Europe with a centre 1.4°C over the lowland near the Caspian Sea. Over Poland anomalies are located meridionally and are dissimilar to the observed one.

Forecast averaged from 20 analogues (Fig. 8b): Positive anomalies with a value of 0.4°C in a centre over the Baltic Sea cover the whole of Europe. Anomalies over Poland are located zonally from 0.4 in the north to 0.2 in the south. Some similarity to observed anomalies exists, however the picture is shifted about 500 km to the south.

Forecast as correction with seven best analogues (Fig 9a): Positive anomalies cover the whole of Europe. In the centre the anomaly has a value of 0.7°C. Over Poland anomalies are located zonally from 0.7°C to 0.5°C. The forecast is higher than the observed value by about 0.4°C.

Forecast with antianalogue extraction (Fig 9b): Positive anomalies cover the whole of Europe with a value of 0.7°C in a centre over the Baltic Sea. The shape and location of the 0.2°C isotherm is very similar to those of the observed 0.0°C isotherm. Anomalies over Poland are placed zonally, however their curvature is bigger than observed. The forecast is too high by about 0.4°C.

Forecast with minimal norm (Fig. 10a): the picture is very similar to that observed. Positive anomalies have two centres with values of 0.5°C: over Scandinavia and over the Barents Sea. The shape of the forecasted 0.0°C isotherm is very similar to the observed one, however its location is shifted 200 km west. As a result the forecast is higher than the observation by about 0.1°C.

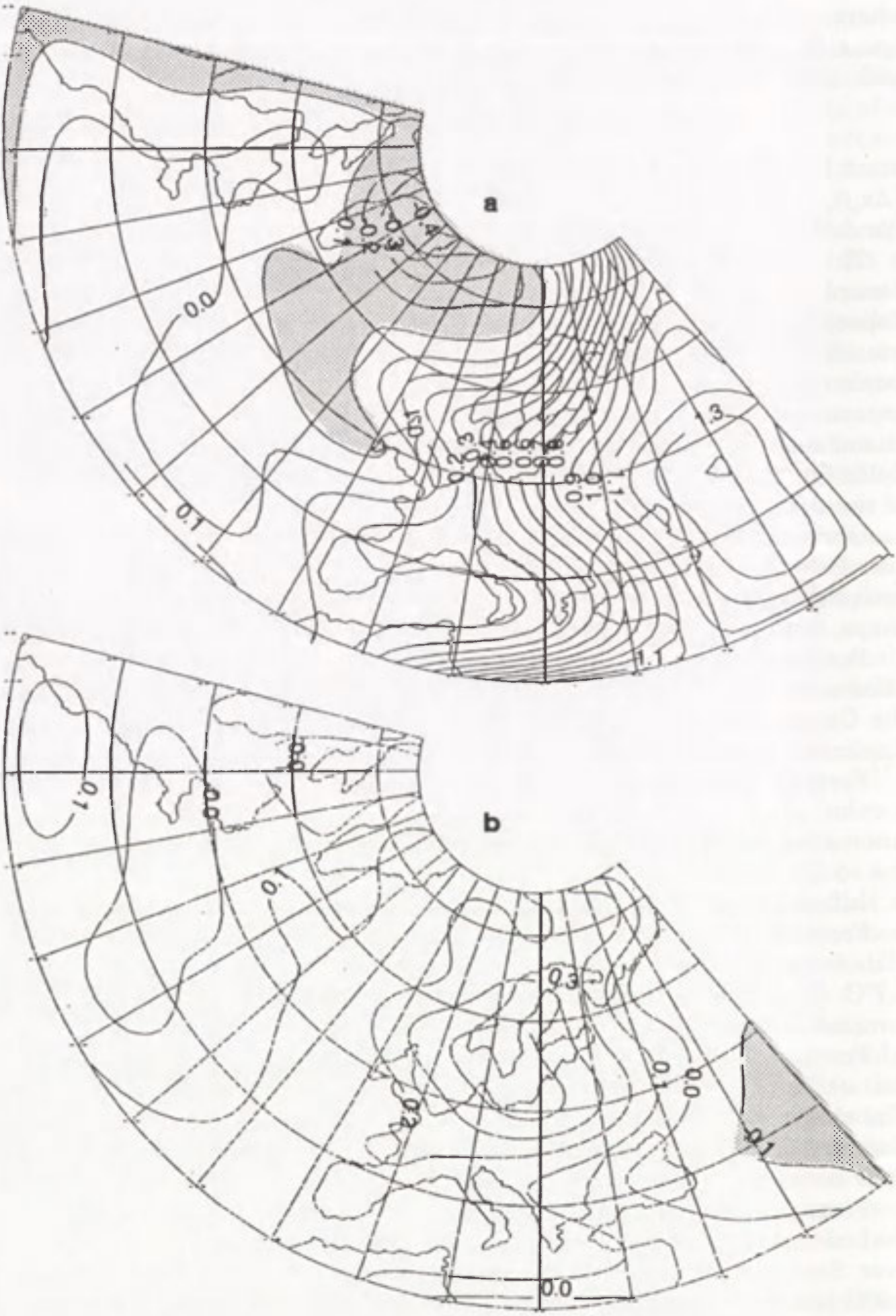

Fig. 8. Air temperature anomaly forecast for cold period (X.92–III.93)
(a) using linear correction by the best analogue, (b) using averaged value of 20 best analogues

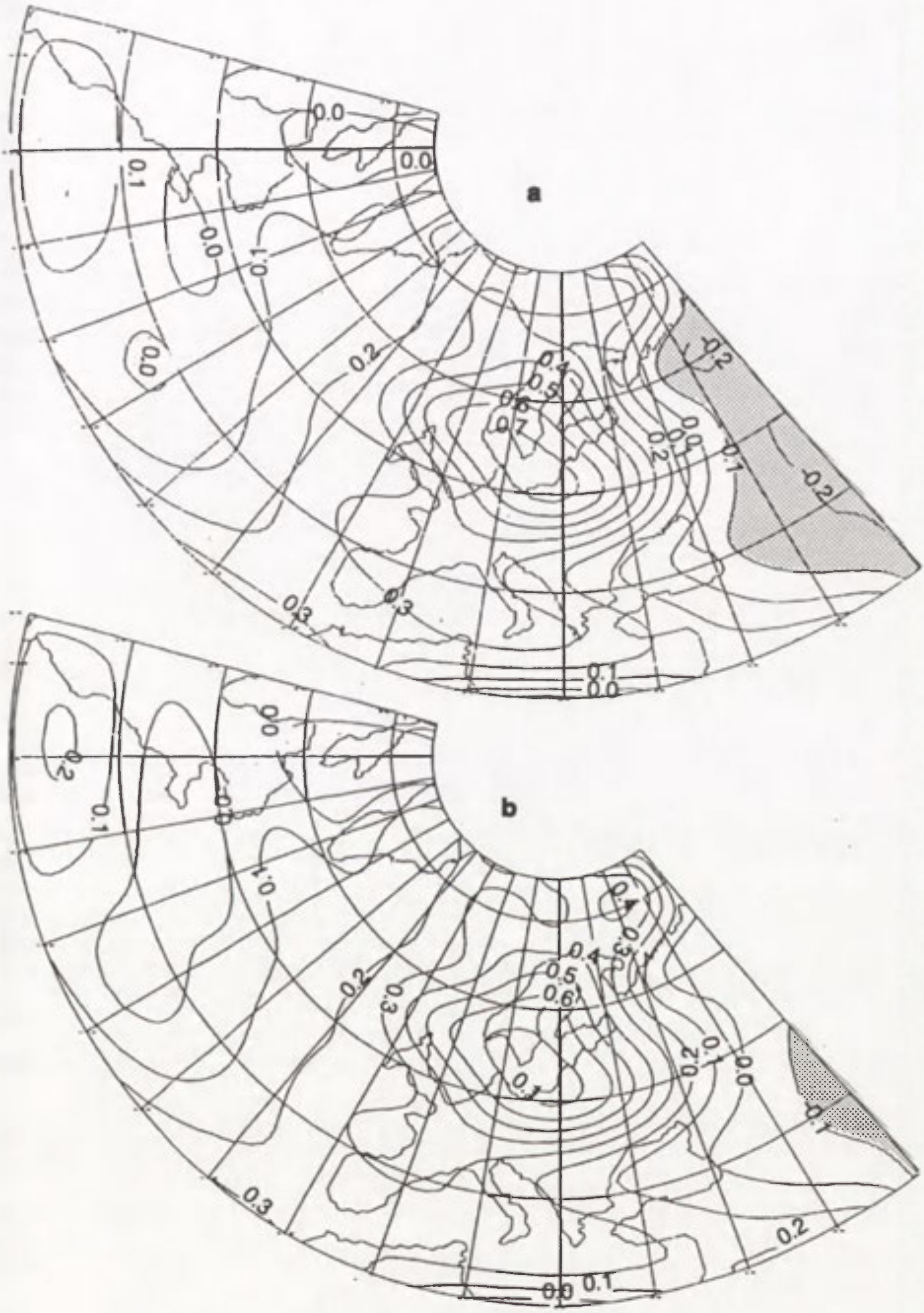

Fig. 9. Air temperature anomaly forecast for a cold period (X.92–III.93)
(a) using a linear correction by 7 best analogues, (b) using an analogue-antilog method

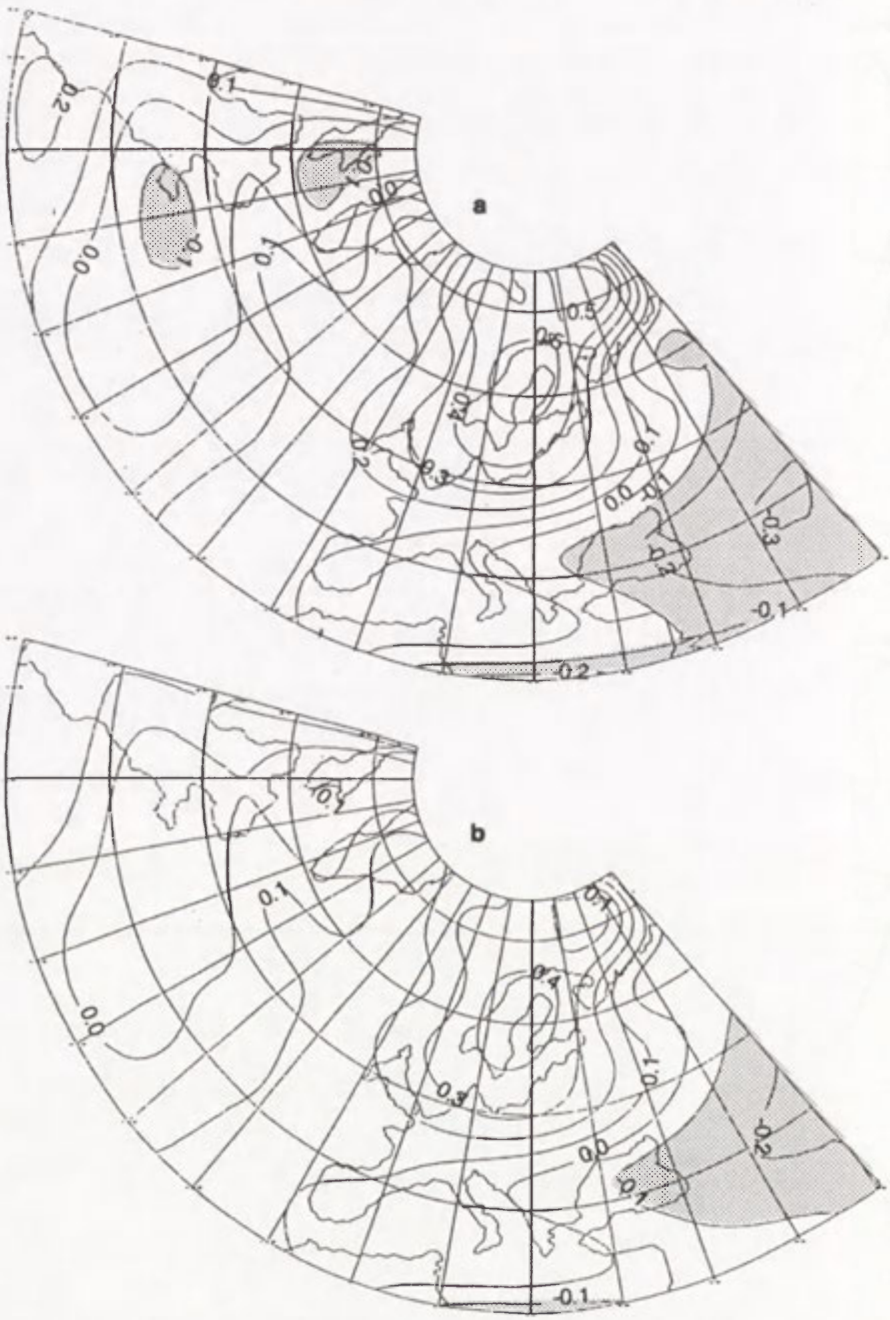

Fig. 10. Air temperature anomaly forecast for a cold period (X.92–III.93) (a) using a minimal norm method, (b) observed anomaly of the air temperature field in period X.92–III.93

CONCLUSIONS AND REMARKS

During an investigation of climate dynamics in the Europe–North Atlantic area different methods were used, tested and modified, finally giving a powerful tool for this kind of research. The development of the method was based on experiences from the theory of dynamical systems. The essence of the method is a reconstruction of a coarse grained dimension of a strange attractor of the Earth climate system on the basis of time series of meteorological data. The best results were obtained by a joint application of the EOF decomposition and Takens method of embedding with a local approximation of a strange attractor trajectory by an analogue method. The presented method has value not only as a research tool but also as a scheme for the prediction of seasonal temperature anomalies, and has since October 1994 been implemented operationally at IMWM (Poland) in the forecast of a half-year air temperature anomaly within the mid-latitudes belt.

Two years earlier this method was introduced for routine testing for the whole area of the former Soviet Union in Russia's Hydrometeorological Centre.

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A STOCHASTIC WEATHER GENERATOR AS A TOOL FOR THE CONSTRUCTION OF CLIMATE CHANGE SCENARIOS

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ABSTRACT: Crop-growth simulation models need long-term daily weather data to assess possible modifications in farm production in changed climatic conditions. Presented here is a stochastic weather generator LARS-WG that provides synthetic long time series of climatic elements. The generator gave an adequate simulation of weather parameters for a selected station in Poland and was next applied to construct climate change scenarios on the basis of UKTR model data.

KEY WORDS: Weather generator, general circulation model (GCM), climate change scenarios, climate variability.

INTRODUCTION

General circulation models (GCMs) are the main tools available today for climate simulation in regard to increased greenhouse gas concentrations. Climate change is expected to have a significant influence on society, the economy and different components of the environment, like the water balance, heat balance, forests, agriculture. energy use nad others. Attempts are undertaken to create projections of regional responses to global climate changes. Most of the climate change impact studies performed at regional scale require daily, long-term weather data (for instance, agriculture). In some studies monthly mean values are not sufficient, so there is a need to create adequate regional climate scenarios for such research. One of the tools helpful in constructing regional climate scenarios is the weather generator providing long series samples of daily climatic records based on observed time series and results from global climate models.

In order to produce climate change scenarios for a selected station in Poland (Zamość), use was made of the LARS-WG model, which is a stochastic weather generator for the simulation of daily climate characteristics.

DATABASE

In order to verify the weather generator and construct climate change scenarios, use was made of observed data in Zamość and output data from the UKTR, for the grid-box containing Zamość.

UKTR is the first transient GCM greenhouse gas experiment which was completed at the Hadley Centre, (Bracknell, UK) in 1991 (Viner and Hulme 1994). The UKTR is a high horizontal resolution model: 2.5° latitude × 3.75° longitude. The initial concentration of carbon dioxide was 323 ppmv in the course of the experiment and was increasing at the rate of 1% per year, resulting in an effective CO_2 doubling after 73 years. Both the control and perturbed simulations were prepared for a 75-year period.

The following data were used in the study:

— a 14-year series (1977–1990) of daily maximum and minimum temperatures, precipitation totals and solar radiation,

— monthly mean values for temperature, precipitation and solar radiation for the control simulation ($1 \times CO_2$) and the perturbed one (past decade of the experiment — years: 66–75),

— daily data on mean temperature and precipitation for the ten-year series for both control ($1 \times CO_2$) and perturbed (past decade of the experiment — years: 66–75) simulations.

LARS-WG: A STOCHASTIC WEATHER GENERATOR

A version of LARS-WG has been developed for MS-Windows on PC. The programme can generate baseline climate and climate change scenarios based on information derived from GCMs for European sites. This version is based on the weather generator described in Racsko et al. (1991), (Semenov et al. 1995).

The stochastic weather model was constructed for risk analysis in crop production, where the risk is associated with the stochastic weather conditions. A long dry or wet series can affect crop growth, influencing yield significantly. Temperature variability can disturb plant development substantially as well.

Data received from the LARS-WG generator based on the present climate should be statistically similar to the observed time series. Therefore, the validation of the LARS-WG model against the observations from Zamość has been performed.

The weather generator, LARS-WG, is based on a serial approach, that is a sequence of dry and wet days (above 0.1 mm). Long dry series allow better simulations using this approach, as opposed to the Markov's chain method of simulating precipitation occurrence, (Richardson 1981). The distribution of other weather variables, such as temperature and solar radiation, is based on the current status of wet and dry series. Mixed exponential distributions were used to model dry and wet series. Daily minimum and maximum temperature and radiation were considered stochastic processes with daily mean values and standard deviations conditioned by the wet and dry series. The techniques used to analyse the process are very similar to those presented in Richardson (1981). The seasonal cycle of mean values and standard deviations was removed from the observation records and the residuals approximated by normal distribution. These residuals were used to analyse time correlation within each variable. Fourier's series were used to interpolate seasonal mean values and standard deviations (Barrow et al. 1995).

Used as the input data for the LARS-WG model was a 14-year (1977–1990) time series of daily data for maximum and minimum temperature, precipitation and mean radiation. The output data from the weather generator contains a set of 30 years of daily data for the same four weather parameters.

In order to compare the observed and generated data, the following statistics were selected: monthly mean precipitation, mean number of wet days, mean length of dry and wet series, daily mean radiation, daily mean maximum and minimum temperature and mean number of days with T max > 30°C and with T min < 0°C. The results of the comparison are presented in Table 1.

TABLE 1. Comparison of observed (obs) and generated (gen) data for Zamość

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Monthly mean precipitation (mm)												
obs.	25.6	20.2	28.6	40.9	56.1	82.2	81.7	65.6	50.5	31.5	33.4	36.9
gen.	22.7	21.7	33.5	37.4	49.4	73.7	83.3	67.8	48.1	34.3	31.1	26.2
Mean number of wet days (day)												
obs.	16.2	14.4	13.9	11.8	13.4	15.3	14.6	12.1	13.2	11.6	14.8	17.9
gen.	13.1	10.8	11.8	9.1	10.7	12.2	12.9	11.1	10.4	9.8	10.1	12.8
Mean length of dry series (day)												
obs.	3.19	4.02	3.84	4.09	3.93	3.20	3.13	3.55	3.67	5.29	3.58	2.80
gen.	3.99	4.19	4.94	5.40	5.10	3.98	3.67	4.11	5.37	4.46	4.75	3.52
Mean length of wet series (day)												
obs.	1.97	2.59	2.06	1.98	2.34	2.18	2.44	2.03	2.26	1.91	2.32	2.39
gen.	2.12	1.90	2.29	2.41	2.28	2.24	3.36	2.08	2.42	1.88	1.86	1.96
Daily mean radiation ($MJ/m^2/day$)												
obs.	1.7	3.1	5.2	8.3	12.3	11.5	12.6	11.4	6.9	4.6	1.9	1.3
gen.	2.1	3.6	6.1	9.7	12.3	13.7	13.1	11.1	8.3	4.7	2.4	1.7
Mean maximum air temperature (°C)												
obs.	–0.7	0.6	6.3	12.8	19.1	21.4	22.5	22.5	17.8	13.0	5.5	1.6
gen.	–0.2	0.9	6.2	13.9	18.7	21.5	22.4	22.0	18.4	12.5	6.0	1.3

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean minimum air temperature (°C)												
obs.	−7.0	−6.2	−1.9	2.1	7.0	10.1	11.3	10.9	7.7	3.5	−0.6	−4.0
gen.	−8.9	−7.6	−3.0	2.1	5.9	9.9	11.3	10.6	6.9	2.8	−1.7	−6.4
Mean number of days with T max > 30°C												
obs.	0	0	0	0	0.1	0.1	0.6	0.5	0	0	0	0
gen.	0	0	0	0	0.2	0.7	0.9	1.0	0.2	0.1	0	0
Mean number of days with T min < 0°C												
obs.	26.0	22.7	19.3	9.4	1.6	0.1	0	0	0.9	6.6	15.9	22.9
gen.	30.2	26.3	22.9	8.6	1.7	0.1	0	0	1.6	7.8	18.9	28.3

Monthly mean precipitation, the mean daily maximum and minimum temperature as well as the radiation generated by the LARS-WG model corresponded with the observed data for Zamość. The characteristics reflecting extreme temperatures above 30°C and below 0°C also complied with observations. The duration of dry and wet series were simulated less accurately in some months due to the limited number of years (14) available for analysis.

The differences between the values simulated by generator and those observed for precipitation, solar radiation and maximum and minimum temperature, were additionally compared to the standard deviation which defines parameter variability. Analysis in Table 2 proves that in only three cases for solar radiation and one for minimum temperature did the differences between the generated and observed records slightly exceed standard deviations.

TABLE 2. Comparison of differences between generated and observed values for climatic parameters (r) and standard deviation (d)

	mean monthly precipitation		mean daily radiation		mean maximum air temperature		mean minimum air temperature	
months	r	d	r	d	r	d	r	d
I	−2.9	14.5	0.4	0.3	0.5	3.6	−1.9	5.0
II	1.5	11.3	0.5	0.7	0.3	4.2	−1.4	4.9
III	4.9	16.3	0.9	1.0	−0.1	3.2	−1.1	2.4
IV	−3.1	22.7	1.4	1.2	1.1	1.9	0.0	1.7
V	−6.7	19.1	0.0	2.1	−0.4	1.5	−1.1	1.5
VI	−8.5	34.8	2.2	2.6	0.1	1.6	−0.2	1.0
VII	1.6	35.3	0.5	2.3	−0.1	1.6	0.0	1.1
VIII	2.2	35.2	−0.3	2.0	−0.5	1.4	−0.3	1.2
IX	−2.4	26.7	1.4	1.2	0.6	2.0	−0.8	0.8
X	2.8	26.2	0.1	1.4	−0.5	1.3	−0.7	2.1
XI	−2.3	17.9	0.5	0.5	0.5	2.0	−1.1	2.1
XII	−10.7	13.6	0.4	0.2	−0.3	1.8	−2.4	1.9

In general, the LARS-WG validation process using observational data from the Polish station in Zamość brought positive results. The model derived statistically adequate series of synthetic daily data which significantly resemble the 14-year series of daily data available from selected stations.

Figure 1 is an example of the comparison of the two (observed and generated) simulations which reflect the daily annual sums of precipitation in Zamość. The length of the dry series is simulated less accurately than that

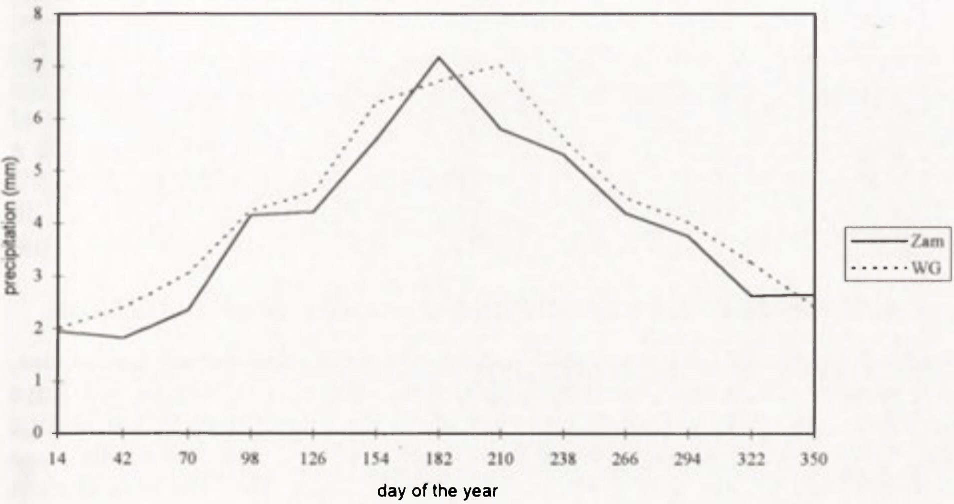

Fig. 1. Observed (Zam) and generated (WG) daily sums of precipitation in Zamość

of the wet series (Fig. 2) but the differences between generated and observed values are rather slight (up to 1 day). Other climatic variables simulated by LARS-WG such as maximum and minimum temperature for both dry and wet series indicated a high degree of similarity to the observed data. Solar radiation is better simulated for the dry series than for the wet series when the differences reach 1 MJ/m^2/day.

CLIMATE CHANGE SCENARIOS

LARS-WG was further employed to assess regional climate change scenarios on the basis of results from the UKTR global model. To generate scenarios LARS-WG uses two parameter files:

— the weather statistics file describing observed climate at a site,

— the scenario parameter file describing changes in means and variations of weather variables, which were derived from UKTR GCM.

The weather statistics file allows for an assessment of dry and wet series distribution parameters, long dry and wet series probability, the average

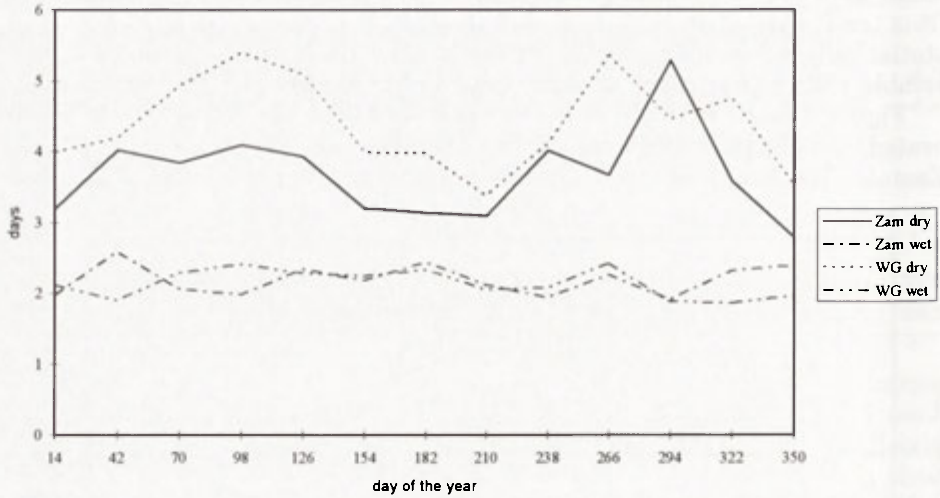

Fig. 2. Observed (Zam) and generated (WG) mean length of dry and wet series in Zamość

length of long dry and wet series, average precipitation during wet series, the average maximum and minimum temperature during dry or wet days and its standard deviations. Information about changes in climatic variability, e.g. temperature variability and the duration of dry and wet spells, was derived from analyses of daily grid-box UKTR data from the last decade (years 66–75) of the transient experiment (on the basis of the grid containing Zamość). The weather statistics file is next employed in the LARS-WG model to create simulations of anticipated changes in climate elements using the scenario parameter file.

The scenario parameter file contains information concerning assumed changes in: daily sums of precipitation, the duration of dry and wet series, temperature and radiation and its standard deviation changes for every month. In the case of the base scenario (used in the LARS-WG validation process), all these parameters are 1 (rain, dry and wet spells, standard deviations of temperature and radiation) or 0 (temperature and radiation).

In order to assess two kinds of climate change scenarios, data in the scenario file were modified on the basis of UKTR projections of perturbed simulation:

— in the first one, monthly mean changes in temperature and changes in relative amounts of precipitation were introduced,

— in the second scenario, changes in temperature and precipitation variability and the duration of dry and wet spells were also incorporated.

Both cases of scenarios were calculated using weather statistics generated using observations.

Information about changes in climatic variability such as temperature variability, and the duration of dry and wet spells was derived from UKTR grid-box daily data from the last decade of the transient experiment (66–75). Within the next stage of this study the regression downscaling procedure will be employed to calculate site-specific changes in mean monthly temperature and monthly relative changes in precipitation.

RESULTS

The climate change scenarios that were constructed using the results of the UKTR model predict an increase in precipitation by ca. 30% in July, according to the mean monthly changes scenario, and by about 45% according to the scenario which presumes weather variability for Zamość as well as a decrease of rain during autumn by ca. 20% and 40% respectively (Fig. 3). UKTR predicts a slight decrease in the number of wet days in Zamość (Fig. 4). The above mentioned predictions indicate that rainfall will be more intensive.

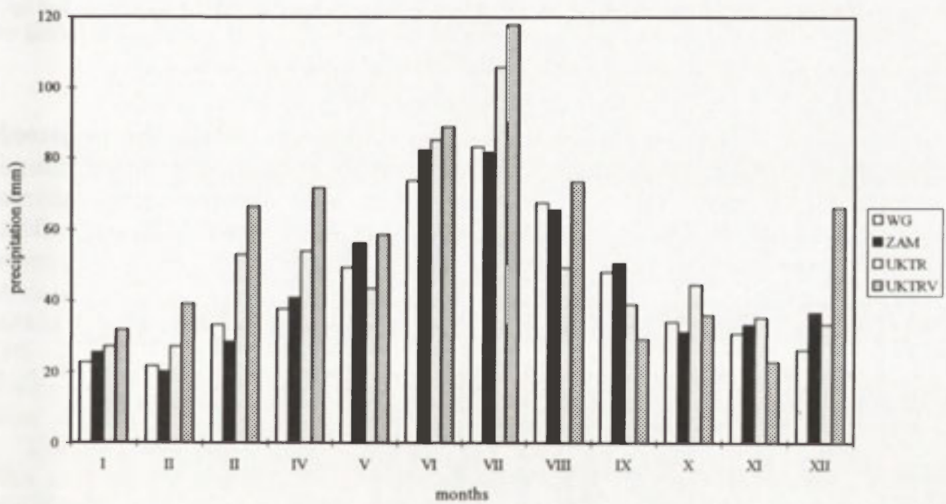

Fig. 3. Mean monthly precipitation in Zamość: observed (Zam), generated (WG) and predicted by UKTR model based on 2 scenarios (mean monthly changes — UKTR and changes including variability — UKTRV)

Radiation will generally be augmented, especially in the summer time — by about 1–2 $MJ/m^2/day$ (Fig. 5).

There are expected changes in temperature extremes: both the mean maximum (Fig. 6) and minimum temperatures will be higher (T max even up to 5°C in winter, T min up to 4°C). The number of days with a maximum temperature above 30°C will increase (up to 6 days in August), whereas days with a minimum temperature below 0°C will decrease in number (even by about 12 days in February).

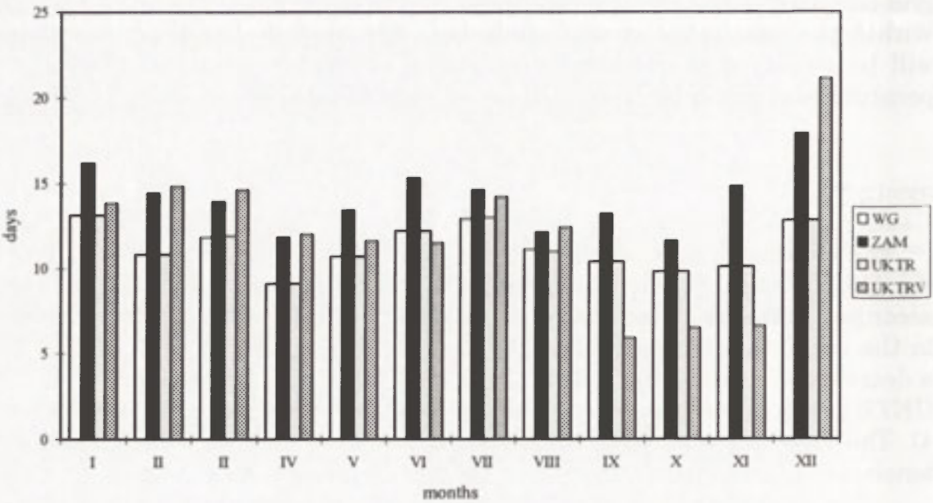

Fig. 4. Mean number of wet days in Zamość: observed (Zam), generated (WG) and predicted by UKTR model based on 2 scenarios (mean monthly changes — UKTR and changes including variability — UKTRV)

According to both scenarios the biggest differences within the projected changes of climatic parameters concern monthly mean precipitation, mean number of wet days and mean number of days with extreme temperatures (> 30°C and < 0°C). These parameters when averaged monthly do not reflect

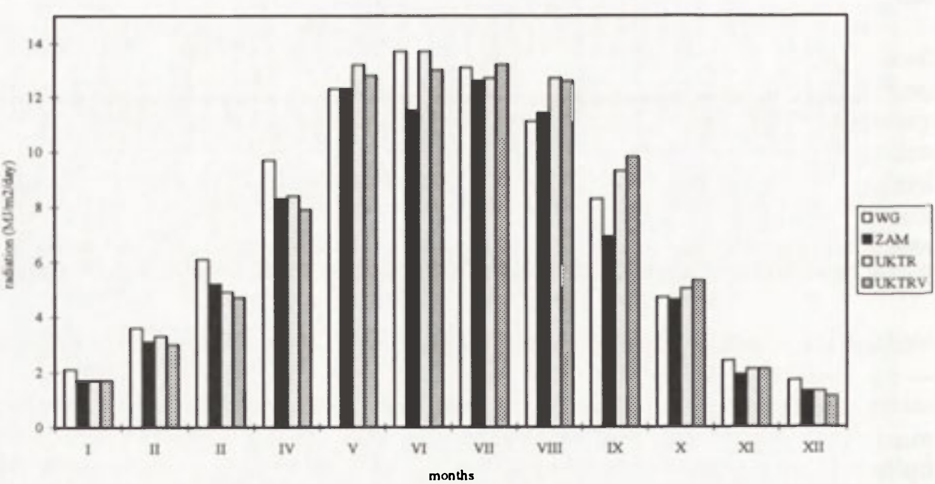

Fig. 5. Daily mean radiation in Zamość: observed (Zam), generated (WG) and predicted by UKTR model based on 2 scenarios (mean monthly changes — UKTR and changes including variability — UKTRV)

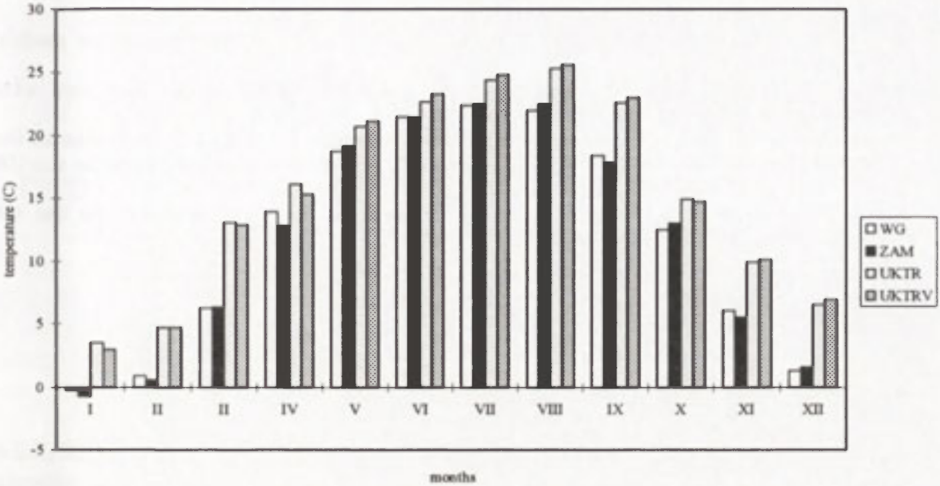

Fig. 6. Mean maximum temperature in Zamość: observed (Zam), generated (WG) and predicted by UKTR model based on 2 scenarios (mean monthly changes — UKTR and changes including variability — UKTRV)

potential changes from one day to another. In the case of other parameters like daily mean radiation or mean maximum and minimum temperature, the results of the two climate change scenarios are very similar.

To sum up the predicted changes in climatic conditions regarding the enhanced CO_2 concentration in the atmosphere in a selected region of Poland, assessed on the basis of the UKTR GCM data, would concern higher temperatures (both maximum and minimum), increased precipitation (by about 12% — monthly mean changes scenario and 37% — scenario including variability annually), slightly enhanced intensity of precipitation and increased solar radiation in the period August–November.

The assessed climate change scenarios can next be applied to crop models (like CERES) that usually require 30-year daily data of primary climatic variables (such as maximum and minimum temperature, precipitation and radiation) and investigate potential changes in plant growth and development and the adaptation of plant cultivation to changed climatic conditions.

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UNDERSTANDING AND ASSESSMENTS OF SOME ASPECTS OF CLIMATE VARIATION IN POLAND

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ABSTRACT: This paper discusses the output of Polish climatologists dealing with climate changes. Some results of the studies carried out by A. Pietkiewicz (1889), R. Merecki (1914), J.P. Rychlinski (1923), W. Gorczyński (1915), H. Arctowski (1934), J. Lambor (1954), E. Romer (1947), W. Okolowicz (1948) et al. are reported.

Climatic forecasts for Poland are presented (with the development of the "greenhouse effect" taken into account). These assume that with doubled CO_2 concentration air temperature in Poland will rise by 2–5°C (Fig. 1). The results of forecasts concerning precipitation are diverse.

Circulation factors take part in forming climate fluctuations. The paper presents a 500 hPa configuration determining thermal and precipitation anomalies in Poland (Fig. 2). The duration of circulation epochs and development stages of continental and oceanic features of Poland's climate were compared (Table 1).

The analysis of many-year meteorological observations reveals quasi-cyclic climate fluctuations whose spectrum ranges from 2, 3–4, 6, 8, 11, 30, 80 and 180-year periods. The two latter cycles — "secular" and "bisecular" — determine falling temperature trends for the nearest future. On the basis of the observed temperature fluctuations their relationship with the 11-year solar cycle was found (Fig. 3).

Research problems concerning the scenario of climate changes for the nearest decades were listed.

KEY WORDS: climatic change, global warming, climate forecasts, climatic cycles, atmospheric circulation.

HISTORICAL OUTLINE

Antoni Szeliga-Magier (1762–1837) professor of Warsaw Liceum, who made meteorological observations for 25 years, can be recognized as the precursor of Polish climatologists. He must have noticed climate changeability, since in the note from 1828 he mentioned the comparison of temperature means characteristic of "earlier" and "later" years (Michalczewski 1980).

However, the first conclusions based on the analysis of multi-year observation series appeared only at the end of the 19th century. A. Pietkiewicz

(1889) who examined the changeability of temperatures and precipitation in Warsaw attempted to determine the periodicity of climate changes by calculating the average duration of negative and positive deviations from the mean value of climate elements.

The persistence of climatological time series was first mentioned by R. Merecki (1914). While examining monthly mean values of temperature he found that "the general character of deviations is homogeneous and tends to maintain the same sign in the first month, the second one and even the third one..." (Merecki 1914 p. 33).

Among monthly values the mean temperature for February turned out to have the closest relationship with the next mothly value — a fact totally supported by contemporary studies.

J.P. Rychliński (1923) studied in great detail many aspects of the space-time changeability of the Polish climate. He presented the periodicity of precipitation changes oscillating in Warsaw with the average period of a 4.2-year cycle. Analysing current observation data we obtain similar results.

W. Gorczyński (1915) published maps illustrating spatial correlations of pressure and temperature changes. He showed that the consistence of thermic anomalies in winter has a far larger range than in summer. The authors of current studies using the same methods (Schuurmans, Coops 1984) obtained similar results, although unfortunately they did not know about W. Gorczyński's much earlier papers.

The climatological research of the past did not overlook the problem of the reasons for climate change. Polish researchers were fascinated by the Sun's influence on the climate.

A critical survey of the views connected with that problem is included in R. Merecki's paper from 1914. Elaborated investigations were conducted in H. Arctowski's school. H. Arctowski and his students thought that somewhere there must be a centre from where the solar influence in the Earth's atmosphere could possibly be observed. This centre — Arequipa — is situated in Peru, 2451 metres above sea level at 16°22'S in a dry, cloudless climate. This place seems to be independent of regional anomalies and shows external impulses (Moniak, Kowalski 1934, p. 16, 17).

Another study by Arctowski presents the climatic impact of the presence of volcanic dust in the atmosphere (Arctowski 1905). In later literature volcanic dust is referred to as one of the causes of climate fluctuations as noted by S.I. Savinow (1913), H.H. Kimball (1918) and W.I. Humpreys (1929). We have not found any reference to Arctowski's paper "Volcanic dust veils and climatic variations", published in 1905.

In 1910 W. Sikorski published the paper "Czy kraj nasz wysycha?" (Is our country drying out?) dealing with the process of steppification.

Descriptions were prepared first by German scientists (von Wex 1873, Seifert 1936) and was dealt with for many years after. The remarks and climatic conditions of that process can be found in the papers of J. Lambor (1954), Z. Kaczorowska (1962) and J. Stachy (1968), the materials of the first Meteorological and Hydrological Conference in Warsaw (Sprawozdanie... 1952) and the special Bulletin of Poznań University from 1964 (Sesja Naukowa... 1964).

A precipitation deficiency was looked for as the cause of steppification. W. Okołowicz (1948) found a zone of precipitation decrease on the axis Berlin — Odessa. Z. Kaczorowska (1962) determined a diminishing precipitation trend in most of the country. However, it did not persist as further studies showed. Looking at the data up to 1980 we can see that precipitation increases. Thus, J. Lambor (1954) may have been right suggesting that it is not the climate but man-made water circulation which is responsible for steppification.

In contrast to steppification were the changes in climate continentality. E. Romer (1947) wrote "O współczesnej oceanizacji klimatu europejskiego" (On contemporary climate oceanity in Europe). Fluctuations in continentality which markedly decreased in the first 30 years of the 19th century are described in L. Horwitz (1929), S. Schneigert (1966), J. Ostrowski (1953) et al.

It is worth mentioning that linking steppification with climate continentalization is common in geographical studies but cannot be justified even if we consider the meaning of the two terms in climatology. It is clear that there are differences between the spatial distribution of steppes and continental climate and the assumed correlation between temporal continentality changes, defined by the annual amplitude of air temperature and steppification progress transforming humidity conditions.

Studies on climate warming in Poland only appeared fairly recently. Indeed on the contrary, the impression is given that climatologists were certain that temperature has had a decreasing trend. Even in 1964 A. Schmuck wondered if the Polish climate was getting colder.

WARMING SCENARIOS

The above mentioned problem of the change of Poland's climate in the light of the greehouse effect and global warming has been discussed only recently.

One of the first papers was written by M. Sadowski and T. Tomaszewska (1990) who adapted the results of American numerical simulations to Polish conditions and characterized the climate of the Noteć estuary, in the change stage equal to the doubled concentration of carbon dioxide ($2 \times CO_2$) in the atmosphere. Concluding, they compared the future climate conditions of middle-western Poland to the present conditions of the Warna or Lyon region.

L. Ryszkowski et al's prognosis (1991) predicts that the Polish climate in the middle of the 21st century will be similar to the present climate of Southern Moravia.

Scenarios of climate and agroclimate in Poland caused by a doubled concentration of CO_2, according to L. Ryszkowski et al. (1993) are made on the basis of an assumed increase of seasonal temperature means and alternate changes (increase or decrease) in precipitation and the transformation of heat balance depending on afforestation changes.

All the 6 scenarios obtained predict warming and a longer vegetation period (even by 100 days) and most of them expect greater moisture deficiency. As a result of warming in the Carpathians the cultivation limit can rise over 400 m and the upper tree line even to about 700 m (Obrębska-Starkel et al. 1994).

M. Gutry-Korycka et al. (1994) presented temperature and precipitation patterns (Fig. 1) all over Poland for a 2 × CO_2 scenario. They were made on the basis of GFDL and GISS numerical models for the general circulation of the atmosphere (GCM). According to the 2 × CO_2 scenario, annual precipitation in Poland will tend to increase by 3–17% in comparison with the mean values observed in the years 1891–1980, and the annual temperature will be higher by 2.8–4.2°C.

The GISS and GFDL models were also used by R. Brazdil (1992) for determining precipitation changes in Europe. On maps of changes in precipitation totals Poland is situated in the zone of slight increase (GISS model) or in the domain of no change (GFDL model). However, only the autumn precipitation increase is statistically significant. The 2 × CO_2 scenario suggests that the temperature in Poland should rise by 2–3°C in summer and 5–6°C in winter (Bach 1988, Brazdil 1991).

Similar predictions are presented on maps of ("2 × CO_2") climate scenarios in B. Obrębska-Starkel and L. Starkel (1991): in summer temperatures should be higher by over 2°C, in winter by 4–5°C, while winter precipitation is to be greater by 75 mm, and summer precipitation unchanged.

The Polish Academy of Sciences' Department of Geophysics attempted to model hydrological processes under the conditions of the scenarios of climatic change, taking into consideration: evaporation processes, surface runoff, underground runoff and retention. This model made it possible to determine the transformation stream flow and changeability coefficients for 22 river basins. Z. Kaczmarek (1993a) states that climate changes following the GFDL scenario may lead to a slight decrease in annual discharge in the central part of Poland, markedly greater water deficiency in the low-flow period and a decrease in soil moisture during the vegetation period.

Z. Kaczmarek and D. Krasuski (1991) noted that, in the central part of Poland unchanged air temperature would be linked with precipitation increases of 10% causing a 23% decrease in river flow. If precipitation is constant, warming by 1°C lowers river flow by 4.5%.

To answer a question as to how precipitation will change as a result of growing climate warming, we can analyze observational data from previous years.

J.U. Lough et al. (1983) compared the precipitation in western and Central Europe in the coldest 20-year period of our century (1901–1920) with that in the warmest 20-year period (1934–1953). On the map of precipitation changes related to warming (the temperature of the Northern Hemisphere rose by 0.4°C) the areas with lower precipitation are more dominant. R. Brazdil (1992) included Lough's map in his paper and added data from Eastern Europe where decreased precipitation was also dominant.

Most parts of Poland also coincided with decreasing precipitation. The precipitaion indicator for Poland in the cold 20-year period 1901–1920 was 4% higher than the many-year mean; in the warm 20-year period 1934–1953 it dropped 2% below the mean.

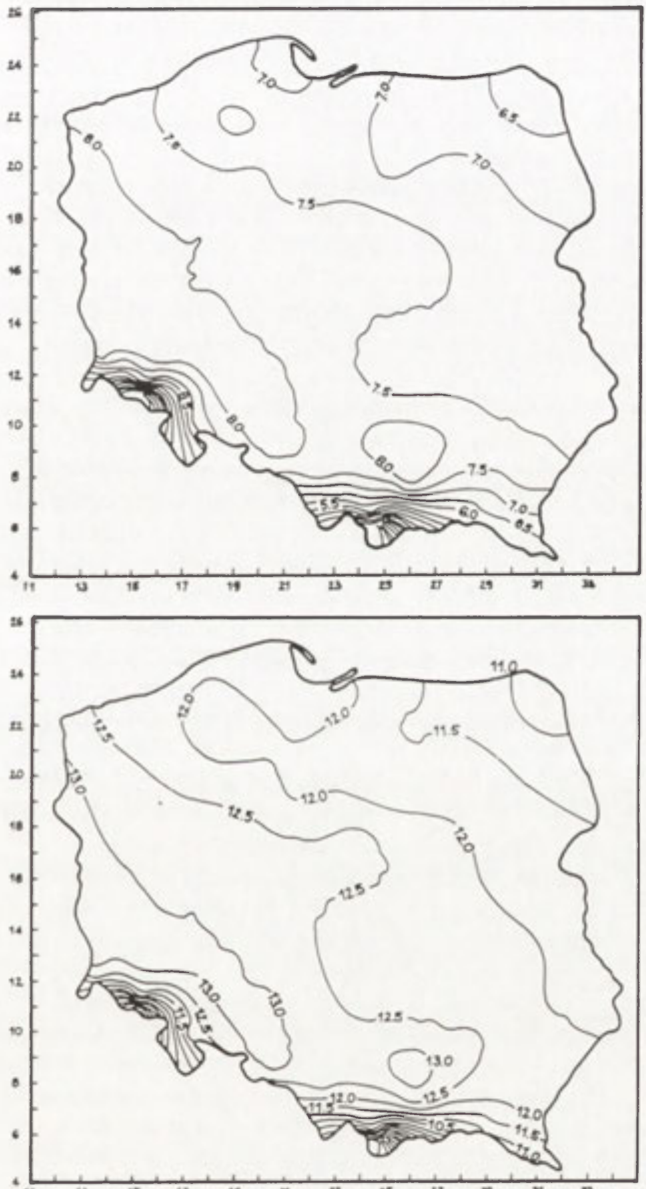


Fig. 1. Annual isotherms all over Poland (in °C) in normal conditions 1961-1990 (upper) and for 2 × CO_2 scenario, GFDL model, according to M. Gutry-Korycka et al. (1994)

At the same time precipitation changeability rose, with the variability coefficient increasing from 10 to 13% (Kożuchowski 1985, 1994a).

It can be seen that the trends for precipitation changes remain an open question. However, in the light of observational data there is no doubt that precipitation variability is tending to grow (Kożuchowski 1994a). An analysis of present and future precipitation changes should pehaps take into account the well-known opinion of M.I. Budyko et al. (1983) that during global warming precipitation decreases at first and increases in the stage of developed warming and air humidity. The above mentioned model and empirical findings seem to confirm such a scenario.

The multi-year observation series can be used to predict regional scenarios of air temperature changes. Scenarios for the "first period of warming" were prepared at the M. Kopernik University in Toruń (Wójcik et al. 1994): seasonal air temperature means in Northern Europe corresponding to the coldest and warmest periods in the northern hemisphere (1881–1900 and 1934–1953) were compared. The mean annual air temperature increase in Northern Europe emerged as 0.9°C. On the basis of the layout of warming isorythms, similar air temperature changes corresponding to the response of seasonal air temperatures to global warming (0.7°C for winter and spring, 0.8°C for summer and autumn) can be taken into account for Poland.

In the inspection of different aspects of global warming relating to Poland some doubts about the so-called "greenhouse effect" must be mentioned. Due to this effect, as J. Paszyński (1990) have stressed, climatology has much greater importance in modern science than before — a fact which raises some reflexions and justifies those doubts to a certain extent.

In the above mentioned review J. Paszyński suggests that the observed CO_2 concentration increase can be of natural origin because the history of our planet has witnessed periods with much greater CO_2 content than at present. The natural cyclicity of air temperature is often emphasised. Its present change phase means growing climate cooling and the observed growing trends can be explained by a response to urban effects, since it is in cities that the majority of meteorological stations are located.

Although the above mentioned opinions cannot be completely disregarded, it is safe to say that the signs of growing warming are really a characteristic feature of the present climate of Poland and Europe, which should not only be attributed to urban heat islands.

Trends for air temperature changes in the troposphere above Europe have been determined by J.L. Pyka (1990). These provide significant empirical evidence for the development of the greenhouse effect. In the years 1961–1985, the air temperature of the lower and middle troposphere grew, while cooling was being observed above the level of 300 hPa, which is consistent with "greenhouse" transformation of long-wave radiation transfer in the atmosphere.

The 1980's and 1990's brought a series of extremely high temperatures in Poland in both summer and winter. In this case however, the irregularities in atmospheric circulation played the main role. Summer air temperature anomalies were caused by meridional circulation patterns, while intensive zonal circulation determined mild winters in Poland after 1988/9.

FLUCTUATIONS OF ATMOSPHERIC CIRCULATION

Atmospheric circulation is an essential link in the process of the formation of climatic changes. Circulation factors are directly responsible for the occurrence of weather changes, year by year climatic changeability and as a result climatic fluctuations.

On local and regional scales circulation can be treated as the cause of climate changes and in particular as the factor determining the geographical diversification of those changes. On the planetary scale, circulation factors can be both the cause and the effect of global changes, and it is difficult to distinguish one from the other.

As far as the observed changes of climatic elements are concerned, circulation makes it possible to explain a significant part of the variance in time series, e.g. a properly-defined gradient of geopotential heights of the 500 hPa surface over Europe and the Atlantic explains over 2/3 of the variance of winter temperatures in Poland (Kożuchowski, Wibig, Maheras 1992). We should point out that this gradient is a very simple index of the circulation affecting the direction advection of air-masses over Poland. The configuration of the pressure field in the middle troposphere, directly related to the macroforms of hemisphere circulation turned out to affect the sign and the quantity of year-to-year temperature and precipitation changes in Poland (Fig. 2).

If this is the case, is it possible to find out the causes of contemporary climatic trends ignoring the changeability of circulation factors?

There is every reason to use climate models as the models of general atmospheric circulation (GCM).

H. Lorenc (1994) took into account the changeability problem of circulation conditions in the studies of observation series. The author gives an explicit circulatory explanation for temperature trends (e.g. increases on mountain peaks), which correlate with growing trends towards eastern and south-eastern anticyclonic circulation.

An evaluation of the influence of circulatory macroprocesses on elements of Poland's climate was made by us (Kożuchowski 1989, Kożuchowski, Marciniak 1988, 1990, Kożuchowski, Wibig, Maheras 1992) by J. Wibig (1993) and K. Kłysik (1994). The series of circulation indexes reconstructed by T. Niedźwiedź (1994b) is of great value for tracing the effects of circulatory fluctuations on the Polish climate.

Studies on the transformation of the circulation of the Northern Hemisphere conducted by B.L. Dzierdziejewski (1978) and A.A. Girs (1977) have led to the separation of a few stages of the so-called circulation epochs in the period beginning at the end of the 19th century up to present times.

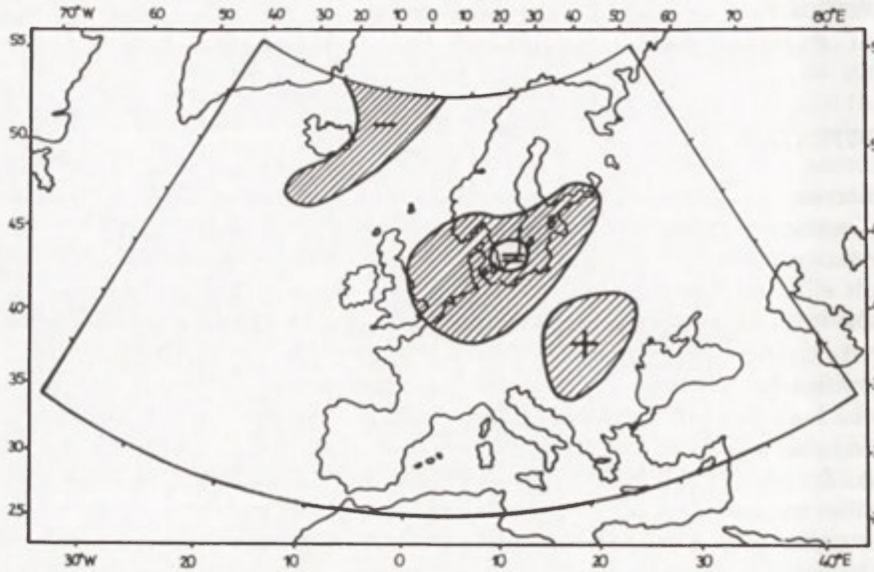


Fig. 2. Geopotential heights at the 500 hPa level correlated with positive (+) and negative (–) air temperature anomalies in Poland and also correlated with precipitation deficiencies in Poland (=)

B. Osuchowska-Klein (1987) also stated that we can speak of the epoch character of the changes in circulation patterns over Central Europe.

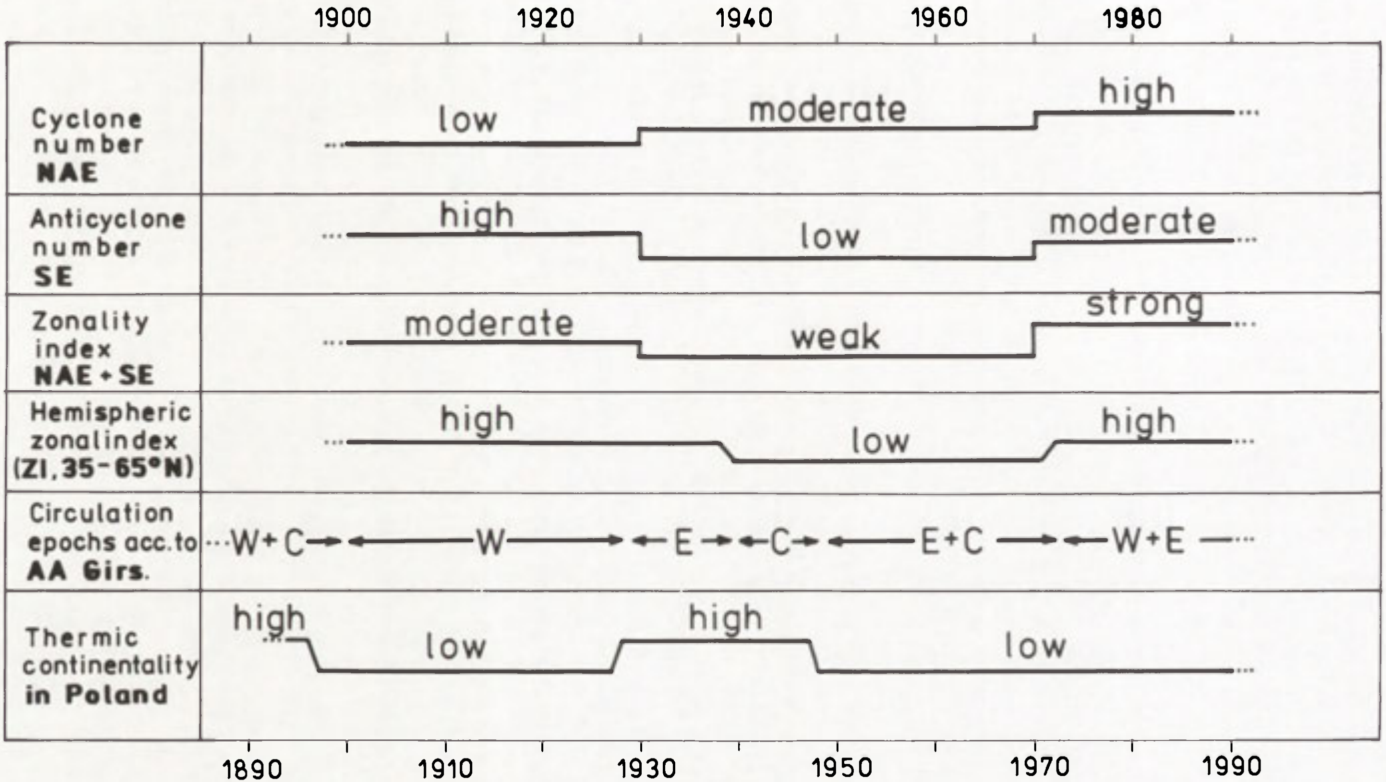
Circulation epochs are reflected in the observed changes in climatic conditions in Poland (Trepińska 1988, Kożuchowski, Marciniak 1993, Ewert 1984).

It is not incidental that A. Girs' (1977) circulation epochs correlate with independently identified epochs of increased oceanic or continental features in Poland's climate (Table 1). Although these are not the only examples, it is clear that the observed fluctuations of climate conditions are developing, first of all, as a result of the changing effects of circulation factors. Another question is that circulation is the internal "way of atmosphere functioning" set in the climate system. However, precise determination of the role of circulation factors in contemporary changes of climate elements would be worth trying. The simplest thing that could be done is the examination of how climate elements change in a definite circulation type.

RHYTHMIC CLIMATE CHANGES

The recurrence of climate events and periodicity of climate elements are the basic problems for climate reconstruction and forecasting. Many attempts have been made to determine the fluctuation periods. The results have varied but in a way confirmed the assumption that each non-period function can be approximated by means of a certain sum of period functions.

Table 1. Circulation epochs and changes in the continentality of climate in Poland



In spectral analysis the observed variance is broken down into elements of different frequencies (Milo 1983). Next, their "power" i.e. their part in the total variance, is examined. To find the cyclic components of the examined variable, only the elements significantly different from the average power of all the components are considered.

The results of periodicity analysis are followed by physical interpretation — definite origin is attributed to particular cycles and there are no strict rules for this kind of interpretation.

Periods of the same or similar length are usually analysed together; e.g. 11-year climate periodicity is associated with analogical periodicity in the activity of the Sun. We can doubt the scientific reliability of such a procedure unless there are any other ways of justifying the relationship of those periods. We can also question if the real origin of the periodicity of the observed series is in fact the reversal of the methods suggested by the methodology of variance decomposition into cyclic components.

In J. Boryczka's method (1979, 1984) some imperfections of spectral analysis (e.g. an arbitriarily-established fluctuation period) were eliminated. J. Boryczka's "deterministic-stochastic model" determines he so-called dense spectrum of cyclic changes according to consecutive regression sinusoids. The sinusoid amplitude indicates the power of the cycles. In J. Boryczka's paper (1993) there is a methodological declaration concerning the interpretation of results and cause-effect relationships. "Oscillation spectra of climate elements (effects) and astronomical parameters (causes) should be similar. Oscillation spectra of air temperature, atmospheric circulation (the link between cause and effect) should be analogical to the oscillation spectra of parameters of the Solar System" (Boryczka 1993).

The presented interpretation has been justified by the following statement: "The presence of several frequency bands of changes (actual periods) both in the spectra of climatological variables and astronomical ones is unlikely to be accidental" (Boryczka 1993).

In the cause-effect model J. Boryczka compares oscillations found in: the group of gravitationally-dynamic parameters of the Solar System, found in the characteristics of the Sun's spot activity and geomagnetic activity and also in climatic variables. Analogies between climatic oscillations and oscillations of gravitationally-dynamic parameters indicate, according to Boryczka, that the location and rotation of planets directly influence the circulation of the atmosphere and the Earth's climate, if analogical oscillations occur in the changes of the Sun's activity the latter factor is considered to be the cause. J. Boryczka has examined 20 fequency bands altogether. Some of them had been known from earlier climatological studies made by different methods. Although the results of dense spectrum studies may be fundamental they will not be discussed here.

However, characteristic cycles of climatic oscillations which constitute certain significant regularity of the observed changeability of our climate are worth mentioning.

It should be noted that "cycles" — in respect of climate fluctuations are commonly called "pseudo-cycles" or merely rhythms of changes which emphasise instability of the periodicity of climate changes. R. Brazdil (1992), for instance, thinks that "because of the instability of the cycles, seen in the changes of their phases and amplitudes, they cannot be used for predicting the properties of time series" (Brazdil 1992). In this light the idea of "the sounding of the future" and also the reconstruction of the past on the basis of cyclic elements are doubtful.

A 3–4-year cycle is typical of the changes of high frequency. K. Takahashi (1980) considers it to be the most widespread period of climatic changes on Earth. Its origin has not been explained yet.

In J. Boryczka's opinion (1993) these short periods are caused by oscillations in the acceleration of the Sun's gravity towards the centre of the Solar System's mass, changing in 3.50-, 4.00- and 5.58-year cycles. The tide forces and gravity forces of the planets change on 3.50- and 3.75-year cycles.

The approximate 3.5-year periodicity was found in: the course of precipitation in Poland (Brazdil, Kożuchowski 1986, Kożuchowski 1985, 1994a), cloudiness in Cracow (Morawska-Horawska 1985), the Vistula runoff (Jokiel, Kożuchowski 1989), and air temperature in the warmest month in Kraków (Kożuchowski, Trepińska, Wibig 1994). There is also 3.5-year component to the changes in the circulation vorticity at the level of 500 hPa over Poland and the Baltic Sea (Kożuchowski, Stolarczuk, Wibig 1994) and the changes in the range of Baltic ice cover (Kożuchowski 1994b). J. Boryczka (1993) found 3–3.5-year cycles to the occurrence of zonal (W) and meridional (C) macrotype changes of hemispherical circulation and cyclonal circulation over Poland.

The approximately 6-year rhythm to changes in climatic conditions is quite characteristic. A significant 6.7-year period was found in the course of precipitation in Poland (Brazdil, Kożuchowski 1986). 6.4-year periods describe fluctuations in the sea level in Świnoujście (Kożuchowski, Stolarczuk, Wiśniewski 1994), and the frequency of occurrence of macroform circulation (C) while 6.3-year periodicity is observed in the frequency of zonal macroforms (W) (Boryczka 1993). A 6.7-year period was determined for the frequency of occurrence of western cyclonal circulation types over Poland (Lorenc 1994).

Due to the similar 6-year periodicity, these rhythms could be related to cyclic changes of the location of the Earth's poles (Bagrov et.al. 1985), while Boryczka (1993) cites the influence of the 5.9-year cycle characteristic of the changes of the velocity moment of the Solar system planets. At the same time it is half of the cycle of Jupiter's revolution.

Special attention should be paid to the 8-year cycles of climate changes noticed in many observation series from northern and central Europe. 8-year changes are mainly characteristic of the winter season.

A significant 8-year rhythm is found in the temperature series of the coldest month in Kraków (Kożuchowski, Trepińska 1993). Winter temperature and the annual temperature means in Warsaw are characterised by similar periods of changes (Kożuchowski, Marciniak 1994).

The extent of ice on the Baltic Sea, according to data going back to 1720, has changed with a 7–8-year rhythm (Kożuchowski 1994b). 7.75-year periodicity was calculated by Miętus (1994) for air temperature means on the Polish coast of the Baltic Sea. A (less marked) 2–3-year cycle together with 7.7-year periodicity explain 21–47% of the observed variance of thermo-iced winter indexes on the coast (Girjatowicz, Kożuchowski 1994). H. Lorenc (1994) found the occurrence of a 7.7-year cycle of temperature changes in 7 long-term observation series covering Poland and the Alps.

Analogical 7.7-year periodicity of temperature changes was reported by J. Malcher and Ch.D. Schönwiese (1987) in several dozen European series. According to B.I. Sazonov et al. (1992) 8-year periodicity is typical of thermo-moisture elements of the climate of the Baltic Sea region and also air circulation of the middle and upper troposphere over that area. The 8-year cycle had been discussed in many other papers and it has also been noticed that its signs intensified after 1920.

The origin of the 8-year rhythm has not been clarified yet. B.I. Sazonov et al. (1992) think it is caused by similar oscillations of the position of the axis of the Earth while M. Miętus (1994) considers it related to the so-called little climatic loop depending on periodic dislocations of the Greenland Sea waters and the occurrence of upwelling phenomenon there.

J. Boryczka (1993) suggests that 7.75-year periodicity of air temperature changes in Europe and also the analogical rhythm of the frequency of zonal (W) and meridional (E) circulation macroforms are synchronic to the cycles of changes in the Sun's acceleration and the extremes of those variables occur more or less in the same years.

I. Charvatova and J. Strestik (1993) include a 7.8-year cycle in the main harmonic group characteristic of the rotation of Jupiter, Saturn, Uranus and Neptune affecting the Sun and forming the 11-year solar cycle. These harmonics have 12.8-, 10- and 7.8-year periods (the so-called "systemic triad"). Identical fluctuations were found in the course of temperatures in Central Europe from 1753. In fact, Czech researchers support J. Boryczka's views concerning the cause-effect relationship between the rotation of the planets and the Sun, the Sun's activity and the Earth's climate. Again, V. Bucha (1991) states that the rhythm is of solar origin caused by periodic changes in corpuscular radiation affecting the circulation of atmosphere in subpolar zones. He lists 2-, 7-, 200- and 800-year cycles of geomagnetic activity and explains the mechanism of transforming circulation forms. As a result of the intensification of corpuscular radiation and growing geomagnetic activity there is an immediate pressure increase in the medium and upper troposphere in aureole zones. Cyclogenesis processes intensify and after 13–27 days warming approaches Europe. On the contrary, when there is low geomagnetic activity, meridional circulation is dominant and this is the reason for severe winters in Europe.

The 11-year solar cycle (discovered in the 1870's) was assigned greater or lesser importance in the occurrence of events on the Earth, in particular in the Earth's atmosphere. It was established that with high values of Wolf's number (80–100), the solar constant grows but the evaluation of its changes are very divergent. Recently the hypothesis has become widespread that turbulences on the Sun and sunspots are determined by the difference between the acceleration of the outer and inner layers of the Sun in their rotation around the centre of the mass of the Solar System. Thus, the configuration of the Solar system planets plays a certain role (maybe significant) in the course of the Sun's activity.

I. Charvatova and J. Strestik (1993) distinguish two types of the Sun's rotation around the gravitational centre of the Solar System: systematic rotations and chaotic ones. The so-called systematic rotation determined by the position of Jupiter and Saturn causes increased solar activity, while chaotic rotation reduces it. The changes in the Sun's rotation have very long cycles of 178.7 years. The 11-year cycle originates from the above mentioned harmonics defined as the "systemic triad". J. Boryczka (1993) states that there are sunspot minima in the years when the centre of mass and geometric centre of the Solar System are on the same line on opposite sides of the Sun. Sunspot maxima — e.g. a secular maximum for 1957 — occur when the two centres lie on the same side of the Sun.

The 11.08-year cycle of Wolf's number and the 11.25-year cycle typical of the change of the angle between the radius vector of the mass centre and the geometric centre of the Solar System are nearly indentical.

In the Sun's activity fluctuations there is a noticeable 12-year cycle ("triad" element) but like the 8-year components, these are clearly visible in the course of climate elements. An approximate 12-year cycle was found by J. Boryczka (1993) in the fluctuation of the indexes of atmosphere circulation (frequency of zonal (W) macroforms, zonal circulation index between 35° and 65°N, frequency of cyclonal types of circulation in Poland). A 12-year periodicity apart from the 8-year one has been noticed in the temperature changes in Europe analyzed by J. Malcher and Ch.D. Schönwiese (1987). The same result is reported by I. Charvatova and J. Strestik who calculated the 12.8-year cycle. It is possible that 12-year periodicity is caused by the influence of the biggest planet — Jupiter — characterized by on 11.862-year period of orbit around the Sun.

Another big planet, Saturn, has an orbital cycle of 29.458 years. Similar cycles appear in the climatic system. The so-called Brückner cycle could possiby belong to them. J. Boryczka (1993) reports that 30-year periods exist in the course of precipitation and the characteristics of atmosphere circulation. B.I. Sazonov and E.K. Malkentin (1993) emphasize the role of planet position in climatic anomalies: exceptionally warm winters in north-eastern Europe in the years 1989–1993 happened during the special configuration of the planets when Saturn, Uranus, Neptune and the Earth were located near a common straight line connecting them with the Sun.

Despite many attempts, it is difficult to prove that climatic fluctuations depend on the 11-year solar cycle, though there are certain regularities bearing a relation between climatic rhythm and the periodicity of sunspots, such as the relationship between temperature oscillations and solar activity. 11-year temperature fluctuations in the coldest month in Cracow were obtained by means of a band-pass filter (Fig. 3). These fluctuations are not closely related to successive solar cycles. Before 1957 they had shorter lengths and were better approximated by a 9-year sinusoid (Boryczka 1993). It can be noted however, that the amplitude of 11-year temperature fluctuations in Cracow was increasing during very strong solar cycles. The correlation between the amplitude of 11-year temperature fluctuations in particular cycles and the maximum annual Wolf's number of each cycle was calculated. The correlation coefficient is 0.43 and is statistically significant.

This correlation confirms a certain indirect role of solar cycles in the formation of climate fluctuations. According to A.A. Girs (1977) meridional

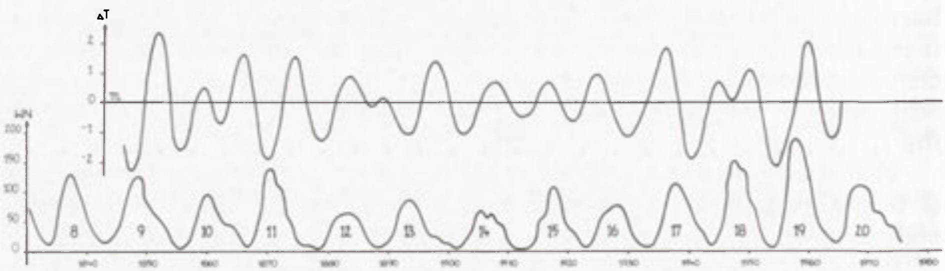


Fig. 3. Fluctuations of air temperature means for the coldest month in Krakow, UJ Observatory (T) and annual means of Wolf numbers (WN). Values of temperature deviation from multi--annual means, 1826-1990 (m) were transformed by means of 11-year band filter. Numbers of solar cycles are given under the curve of Wolf numbers

circulation forms are dominant with the growing secular cycle of solar activity. Meridional circulation brings about both the cold and warmth advections, thus the amplitude of temperature fluctuations in winter is growing.

Long cycles, the so-called secular cycles and the cycle of 178.7 years and their climatic counterparts in particular, should be treated as a hypothetical form of long-term climate fluctuations. Their recurrence have not been confirmed by existing series of instrumental observations.

I. Charvatova and J. Strestik (1993) stress the compatibility of warm periods, high solar activity and the systematic type of the Sun's rotation. Maximum temperature means in central Europe, the USA and Canada were in the years 1760–1780 and 1940–1950 and minimum means in the years 1830–1840. The systematic Sun's rotation occurred around 1760 and 1940; chaotic rotation related to low solar activity (Dalton's minimum) occurred throughout the first half of the 19th century. In those times (19th century) the temperature in central Europe was 0,7°–0.8°C lower than in the 1760s and 1940s. Similar dates for temperature extremes were found for the Arctic Circle: maxima around 1760 and 1940, minima in the 1840s. In the nearest decades, in accordance with the long-term cycle — the Sun's rotation will be chaotic and its activity low; so natural cooling of the climate is being predicted.

J. Boryczka (1993) states that the Sun's activity (Wolf's number) has a 186-year cycle and that the four major planets — Jupiter, Saturn, Uranus and Neptune — have identical positions in relation to the Sun every 171.4 years.

Using Manley's series — of air temperatures in central England starting in 1659 — Boryczka discovered the 175.9-year cycle. The corresponding cycle for air temperatures in Warsaw (with data since 1779) is 195.17 years and the temperature increase in Kraków (with data since 1826) is probably an element of the same multi-annual cycle. Like the above mentioned Czech scientist, J. Boryczka (1993) predicts cooling in the coming century. The overlap of a secular air temperature cycle (of 89.67 years) and a bisecular cycle (of 195.17) will decrease the air temperature in the 21st century, in Warsaw to 5.9°C (c.f. the long-term mean of 7.5°C). The error associated with Boryczka's approximation is ± 1.3°C.

It is obvious that climatic forecasts based on the analysis of cyclicly changing "natural" climate factors are in contradiction with the predicted warming depending on the changes of the atmosphere content. Researchers who predict cooling state that it will be moderated by the greenhouse effect, but the basic question of contemporary climatic trends remains open.

Both hypotheses provoke "troublesome" questions such as: is the convergence of two-thirds of temperature and solar extremes not accidental? Why are the secular and bisecular climatic cycles not more reliable than short-term cycles which have turned out to be unreliable many times? Were precisely determined climatic cycles calculated on the basis of reliable homogeneous observation data? In the case of the Warsaw series it would be difficult to answer the latter question in the affirmative.

The hypothesis of global warming also raises some doubts; of which some are quoted by H. Lorenc (1994). They have been presented in the chapter dealing with warming scenarios.

The problem of "climatic cycles" i.e. periodic components in observed climatic variability on which the special attention of climatologists is focussed, requires precise definition of the rules for the interpretation of climatic oscillations. In fact they are more rigorous than is thought.

Firstly: cyclic components of the spectrum only formally correspond to the real form of climatic variable. The observed changeability can, but does not have to, result from the overlapping of cyclic oscillations. The oscillations found in the spectrum remain a scientific hypothesis.

Secondly: determination of the actual spectrum component should be accompanied by an indication of the physical process whose functioning is also of a cyclic nature. Obviously, such an explanation requires the application of a certain independent method.

Thirdly: the convergence of cyclic changes could prove an inefficient basis for explaining and finding cause-effect relationships. In physical systems there are some cases of the generation of processes of a cyclic character by aperiodic factors (e.g. circulatory convection).

Analogies between the spectrum of climatological time series and the light spectrum can be apparent: the problem consists in showing "colours" which appear while splitting light and which are sought in the "noise" generated by the climatic system.

FINAL REMARKS

1. The review of many publications, of which some were quoted in this paper, shows the long tradition of Polish climatology in the field of climate changeability. The studies have been widened by attempts at modelling and forecasting the climate. However, there is no explicit strong view on the climate of the future — the prospects for its changes in the coming decades. Ignoring certain doubts concerning the concept of global warming, some problems of so-called regional interpretation — the specification of planetary changes with reference to the country's area — should be mentioned. There is a great need for the realization of a National Climatic Programme which — as the authors of the project say "has become a must at present not only because of the needs of the country concerning environmental protection but also because of international obligations" (Niedźwiedź 1994a).

2. As far as the methodology of climate description is concerned there is an assumption that random processes affecting the climate are of a stationary nature. Process evolution is not so slow as to be neglected (Kaczmarek 1993b).

3. The contemporary climate of Poland is characterized by increased instability. Since the late 1980s a distinct concentration of climatic anomalies has been observed. A rising trend towards time-dependent changes in the variability of some climate elements (precipitation) is also stated.

4. The Polish climate is especially sensitive to the influence of atmosphere circulation and also to changes on the planetary scale. Recent warming coincides with the highest (since the end of the 19th century) intensity of zonal circulation in the Northern Hemisphere. It is thus possible to speak about a certain individualization of the climatic trends of Poland.

5. Attempts at modelling the climate of the future, assuming a doubling in the concentration of CO_2 in the atmosphere, indicate considerable warming of the climate (even by a few degrees by the middle of the 21st century) and unstable humidity conditions with the possibility of precipitation deficiencies. The analysis of long-term climate oscillations shows downward trends for air temperature. Such a trend could weaken the effects of the developing greenhouse effect but it is doubtful if the current rhythm of climatic changes will persist in the conditions of global warming.

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EFFECTS OF REGIONAL AND LOCAL CLIMATIC CONTROLS ON MULTIANNUAL AIR TEMPERATURE SERIES

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ABSTRACT: Contemporary climatic changes occur on global, regional and local scales. On each of these, changes are shaped by a set of various climatic controls, whose concurrent action has various effects on the functioning of climate in time and space. The climate of the Raba River valley in the period 1971–1992 is presented in this study as an example of the changes that can take place in the character and structure of a local climate. The regional scale trends of air temperature changes for the Carpathian Foothills are presented along with local scale transformation of climatic relations in the Foothill valleys produced by the construction of a reservoir. It is also demonstrated how an analysis of trends in air temperature changes can help detect inhomogeneities in observation series made for different types of topoclimate.

KEY WORDS: topoclimate, climatic change, data homogeneity, human impact on climate.

INTRODUCTION

A reliable estimation of trends in climatic changes based on instrumental observations requires that the analyzed series be homogenous. According to the simple and convincing definition of Tuomenvirta and Drebs (1994), this means that the observation series cannot be disturbed by local factors, mostly resulting from human activity, such as urbanization, modification of water systems and changes in vegetation cover. The series should reflect climatic changes over comparatively large areas resulting from alterations in atmospheric circulation, in the solar constant and in the chemistry and transparency of the atmosphere.

The analysis of observation series homogeneity carried out with information from metadata sets in Finland (Heino 1994) and the Czech Republic (Brázdil 1991; Brázdil, Budiková 1994) showed how important for the quality of source materials are, among other things, changes in the methods used for observations of meteorological factors such as equipment and location measurement stations, as well as the choice of the observation period for which the trend in mean values and the extreme values are to be determined.

These and other known factors disturbing the homogeneity of observation series can lead to wrong interpretation of atmospheric states and processes occurring in a given region in different periods. The choice of a station representative of a given region can therefore be regarded as appropriate only if the determined trends for multiannual changes of selected climatic parameters are affected neither by the above listed objective factors nor by local factors.

The aim of this study was to show how the construction of a reservoir in a Foothills valley affects the break of homogeneity of the series, and how difficult it is to identify these changes. They also provide evidence as to how apparently small changes produced by the damming of the river lead to qualitative changes of climate. Thus, this article is a contribution to work on the problem of the reliability of climatic trend determinations made in Eastern Europe in this century.

AIM OF THE STUDY, CHARACTERIZATION OF THE REGION UNDER EXAMINATION

The aim of the study was to determine the ways in which the construction of a reservoir in the Raba River valley in 1987 disturbed the homogeneity of the air temperature series recorded for the Carpathian Foothills over the period 1971–1992. From the mid-1960s the Department of Climatology of Kraków's Jagellonian University has been carrying out climatological studies in Gaik Brzezowa, a representative of the upland topography areas of the northern side of the Carpathians (Niedźwiedź 1973, Ociepka 1994, Makowska 1994, Trepińska 1994). The mesoclimate of this region is shaped by an atmospheric circulation (Niedźwiedź 1975, Obrębska-Starklowa 1995). Because the observation sites are located in the area of one set of atmospheric processes it could therefore be assumed that the general climatic background is uniform for the whole studied region. Consequently, the series of air temperature data from the station in Gaik Brzezowa should reflect the effects of warming observed in Central Europe from the mid-1970s (Niedźwiedź 1993, Bednarz et al. 1993, Brázdil 1994). On the other hand, parameters of the local climate can change in relation to the background upon the action of factors such as the natural relief of the area, considered to be the most important among other factors, and the reservoir, together with the concave topography of its location. The effects of the former were revealed before the construction of the reservoir in the spatial distribution of thermal and air humidity conditions, as the concave topography produces exceptionally strong and frequent inversions of air temperature.

The set of data concerning air temperature recorded in Gaik Brzezowa in the years 1971–1984 therefore reflects the co-effects of the atmospheric circulation and topography, whereas in the years 1988–1992 the effects produced by the reservoir have to be added in. The reservoir has average surface area of 950 ha and an average depth of 28 m. Noteworthy is that the last five years have been marked by a noticeable upward trend for temperature recorded in the whole of Central Europe (Brázdil 1991) and also on the northern side of the West Carpathians (Obrębska-Starkel et al. 1995).

SOURCE MATERIALS, METHODS

From the outset of the meteorological observations carried out in Gaik Brzezowa, the base station was the Terasa measurement site (altitude 259 m, Table 1) located on an overflood terrace in a widening of the Raba River valley resembling a basin. Because of the planned construction of the reservoir, the new Kopiec base station was founded on the lower Foothills ridge (altitude 302 m) in 1981. In the period 1981–1984 the stations operated in parallel. The Zbocze station is the only station whose location was not changed, although after damming of the Raba the relative height of its location became 12 m above water level. In 1988 the Brzeg station (altitude 272 m) was founded in the immediate vicinity of the reservoir (Fig. 1).

TABLE 1. Location of the stations used in the present paper

	Station	Altitude (m)	φ	λ	Period of observation
Gaik	Terasa	259	49°52'N	20°04'E	1971-1984
Brzezova	Zbocze	283			1971-1992
	Kopiec	302			1982-1992
Kraków	Botanical Garden	206	50°52'N	19°58'E	1971-1992
Szymbark		315	49°38'N	21°07'E	1971-1992

Analyzed in this paper are the trends to changes in mean annual air temperature and its mean annual extremes from both the measurement sites at Gaik Brzezowa. Durations of the "partial" series composing the base-station series (Table 1) were also taken into account. The values used in this analysis are based on true means calculated from the data recorded by thermographs. The thermographs were placed in shelters at a standard height above ground level. Fluctuations in air temperature were presented with the use of five-year moving averages. The magnitudes of trends were computed from the mean annual values of temperature parameters in the form of linear regression equations. The seasonal trends underlying changes in the above mentioned thermal parameters were also taken into account, for the effects of the reservoir on thermal conditions were recognized through changes in the spatial distribution of mean temperatures of transitional seasons, autumn in particular. The seasons of the year also show different increases in mean hourly air temperature at night and attenuation of the occurrence of air temperature inversions in the area of the Raba River valley (Obrębska-Starklowa, Grzyborowska 1995). This transformation of thermal conditions gave rise to a change in the spatial structure of topoclimates starting from

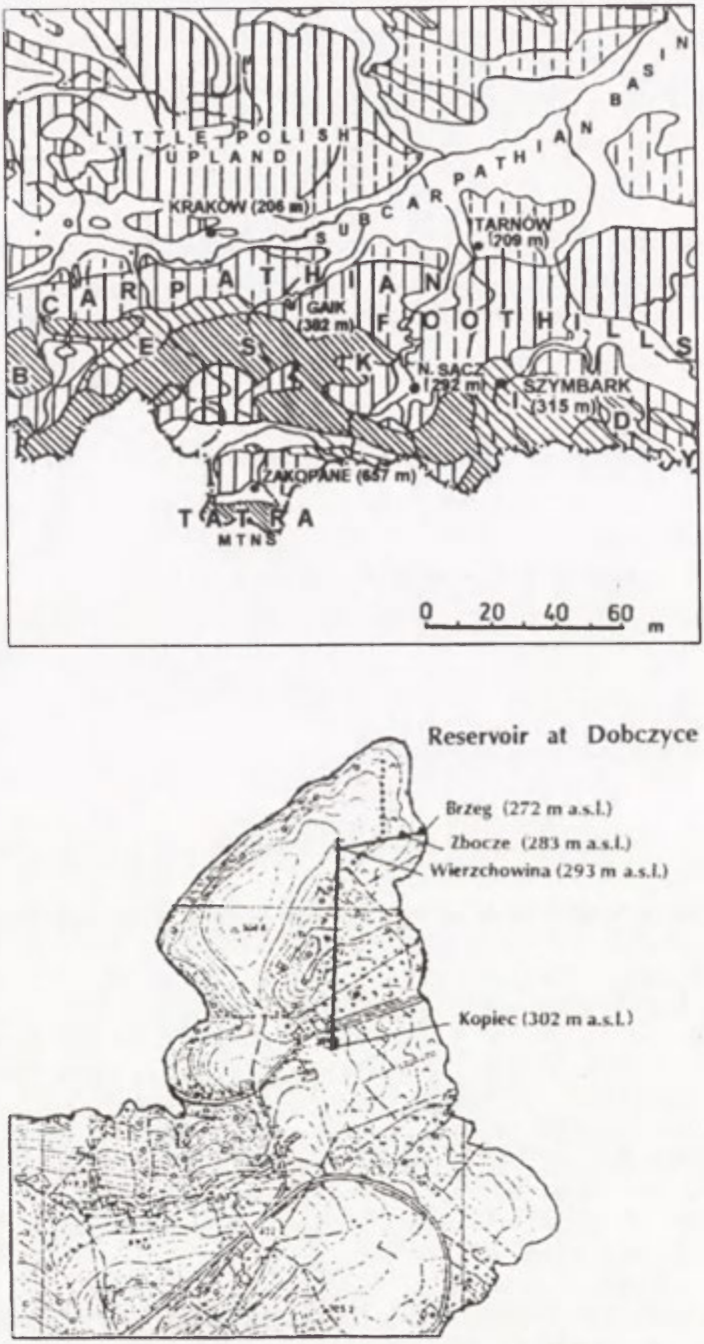

Fig. 1. Situation of the area under investigation and location of the topoclimatic sites in the Raba river valley

1988. This is to say that there arose the allochtonous topoclimate of the Foothills ridge and the topoclimate of the valley slopes in the direct vicinity of the reservoir (Obrębska-Starklowa 1995, Obrębska-Starklowa et al., in print) in relation to the energy balance and matter cycling in the water environment. In the topoclimate of the slopes only in the daytime could certain differences in mean hourly temperature between Zbocze and Brzeg (in favour of the former) appear as a result of insolation. At night, however, the whole of the valley was affected by the reservoir, and the wedge of the valley served as a clear-cut border between the topoclimate of the Foothills ridge and that of the slope (Obrębska-Starklowa 1995).

TRENDS TO AIR TEMPERATURE CHANGES IN GAIK BRZEZOWA OVER THE PERIOD 1971–1992

The trends in multiannual changes in both mean annual temperature in Gaik Brzezowa and mean seasonal temperature were compared with those recorded at the stations in Kraków (Botanical Garden, altitude 206 m) and Szymbark (altitude 315 m). The former of these represents conditions typical of an town centre, with all the effects produced by the development of an urban heat island. Since 1951, a constant increase in the air temperature difference between Kraków (in particular its built-up centre) and out-of-town stations has been observed (Lewińska et al. 1982, Lewińska 1987). This is why the series of data from Kraków, though reliable in quality, can only be used as a source of general information on the course of changes in thermal conditions. However, the observations were used in this study, as they remain the only available data on this part of the foreland of the Carpathians, because numerous meteorological state-network stations in the area have been closed down. The Szymbark meteorological station lies about 100 km from Kraków. Similarly to Gaik Brzezowa, it represents the Carpathians Foothills, and more particularly their eastern part, which have a somewhat different system of basic geomorphological units.

The analysis of air temperature changes over the examined period of time was performed using two procedures. In the first, the series recorded at the base station for the whole period 1971–1992 was considered. It was assumed that the transfer of the station 43 m higher along the vertical profile, from the initial place of concave topography to a place of convex topography in the hypsometric vertical zone 200–300 m above sea level, resulted only in a small increase in mean annual air temperature, equal to 0.2°C. The above was a preliminary and formalistic approach to the changes under examination, because the locational change of the station could simultaneously have produced an increase in mean annual minimum air temperature by 1.4°C and a decrease in mean annual maximum air temperature by 1°C.

The second procedure saw trends underlying air temperature changes analyzed separately for Terasa and Kopiec stations, which both served as base station in the years 1971–1984 and 1982–1992, respectively. The magnitudes of temperature changes per decade calculated for these subperiods were treated as proof that a different set of environmental factors affected the local climate. The trend for air temperature changes was also determined at Zbocze station (altitude 283 m), whose location was not changed over the period 1971–1992.

The preliminary study of the homogeneity of the series of annual air temperature at the stations in the Raba valley was carried out by the method of differences (Table 2). The corresponding observation series from the Kraków-Botanical Garden and Szymbark stations were assumed to be reference points. Differences in mean annual temperature between the above reference points were also compared with each other to reveal the growing intensity of the urban heat island. The progression of differences between Kraków and Szymbark did not show a break in homogeneity. Likewise, an inhomogeneity of the series was not found for differences between the base station in Gaik Brzezowa and that at Kraków although the history of observations in Gaik Brzezowa provides evidence for it.

TABLE 2. Differences in the mean annual air temperature (°C) for some chosen pairs of meteorological stations in the years 1971–1992

Year	GB–K	Z–K	S–Z	S–GB	K–S	GB–Z
1971	–0.7	0.1	0.8	0.0	0.7	–0.8
1972	–0.7	–0.5	0.4	0.6	0.1	–0.2
1973	–0.7	–0.5	–0.4	–0.2	0.9	–0.2
1974	–0.6	–0.2	–0.6	–0.2	0.8	–0.4
1975	–1.3	–0.5	–0.3	–0.1	0.8	–0.2
1976	–0.7	–0.6	–0.3	–0.2	0.9	–0.1
1977	–0.7	–0.3	–0.5	–0.1	0.8	–0.4
1978	–0.8	–0.5	–0.6	–0.3	1.1	–0.3
1979	–0.7	0.2	–0.9	0.0	0.7	–0.9
1980	–0.6	–0.2	–0.6	–0.2	0.8	–0.4
1981	–0.7	0.1	–0.8	0.0	0.7	–0.8
1982	–0.9	0.1	–1.2	–0.2	1.1	–1.0
1983	–0.6	–0.1	–1.0	–0.5	1.1	–0.5
1984	–0.7	–0.4	–0.3	0.0	0.7	–0.3
1985	–0.6	–0.1	–0.8	–0.3	0.9	–0.5
1986	–0.4	0.0	–0.8	–0.2	0.8	–0.4
1987	–0.6	0.2	–0.7	–0.3	0.9	–0.4
1988	–0.5	–0.1	–0.9	–0.5	1.0	–0.4
1989	–0.4	–0.1	–1.1	–0.8	1.2	–0.3
1990	–0.2	–0.1	–0.9	–0.8	1.0	–0.1
1991	–0.5	–0.2	–0.9	–0.6	1.1	–0.3
1992	–0.3	–0.1	–1.4	–1.0	1.3	–0.4

GB — Gaik Brzezowa, K — Kraków, S — Szymbark, Z — Zbocze.

The temperature trend over the observation period was therefore studied assuming that a given set of climatic controls affects specifically the development of variability of a studied element and of the distribution of its value in time and space (Cehak 1977). On the basis of linear regression equations describing the trends for selected air temperature characteristics, it was estimated that the mean air temperatures in Kraków and Gaik Brzezowa as well as in Zbocze showed similar trends (Table 3). The average increase in the years 1971–1992 ranged from 0.9°C at Zbocze to 1.1°C in Kraków. Similar were the values for temperature increase over the period from spring to autumn; at the Raba valley stations this increase was higher by 0.3–0.5°C than in Kraków. In Szymbark the increase in mean annual air temperature over the studied period was found to be 0.3°C. For seasons it was detectable only in summer and autumn, and was determined to be 1.0°C and 0.6°C, respectively.

TABLE 3. Average changes in the mean air temperature (°C) on the sites in the Raba valley, in Kraków Botanical Garden and in Szymbark

a) in the period 1971-1992

Season	Kraków Botanical Garden	Gaik Brzezowa base station	Gaik Brzezowa Zbocze	Szymbark
Winter	0.7	0.7	-0.1	–1.5
Spring	0.4	0.7	0.6	0.1
Summer	1.3	1.6	1.7	1.0
Autumn	0.9	1.4	1.2	0.6
Year	1.1	1.0	0.9	0.3

b) in the subperiod 1971-1984 (A) and 1982-1992 (B)

Season	T_{mean}		Tmax		Tmin	
	Terasa A	Kopiec B	Terasa A	Kopiec B	Terasa A	Kopiec B
Winter	–2.6	6.9	–4.6	6.7	–4.0	5.9
Spring	0.0	0.6	0.1	1.4	0.0	0.8
Summer	0.3	2.1	0.3	1.6	0.4	2.5
Autumn	0.4	0.5	0.5	1.2	0.4	1.4
Year	–0.7	2.6	–0.7	2.1	–0.9	2.8

By taking Szymbark as a station representative of this part of the Carpathians Foothills and remaining mainly under the influence of natural controls, it was possible to confirm the opinion of Schönweise et al. (1994) that, in comparison with Western Europe and Scandinavia, Poland is a country whose trends in air temperature changes are little developed, especially in spring. This is why the greater increase in air temperature in Gaik Brzezowa and Kraków should be treated as a result of human activity.

The trends for air temperature changes in winter (Table 3) need to be discussed separately. Over the period 1971–1992, the mean annual temperature in winter increased by 0.7°C in Kraków and Gaik Brzezowa. At Zbocze station it kept nearly the same value, whereas in Szymbark it dropped by

1.5°C. As reported by Trepińska (1994), the mean air temperature in Szymbark in November, December and February decreased considerably i.e. by –0.67°C/decade, –0.27°C/decade and –0.48°C/ decade, respectively. In Kraków a considerable decrease occurred only in November (–0.49°C/decade). An increase in the mean temperature of winter months was noted only at the base station in Gaik Brzezowa (1.01°C/decade) and in Kraków (1.27°C/decade) mainly in January.

Over the examined period, the greatest increases in mean air temperature at all the stations occurred in summer (the maximum was at Zbocze — 1.7°C). The increases were also great in autumn: 1.4°C in Gaik Brzezowa and 1.2°C at Zbocze (Table 3).

Compared to the whole period 1826–1990, the increases in mean monthly air temperatures in the period 1971–1992 were considerable (Trepińska 1994). They were very great in January both in Kraków (1.27°C/decade) and in Gaik Brzezowa (1.01°C/decade) as well as in June and August at all the stations (within the range 0.43–1.08°C/decade) and in December in Kraków (0.69°C/decade). These rapid increases for 1971–1992 as compared with 1826–1990 are most probably a result of an overlapping of the trend in general circulation and local effects on topoclimate.

"Smoothed" using five-year moving averages, mean annual air temperature and mean annual temperature extremes at Zbocze station (Fig. 2, 3) allowed for it to be concluded that the period 1971–1984 was characterized by little variability of thermal conditions around the mean values for the longer period of time (see Table 4, Fig. 2, 3). Only "positive" and "negative" deviations from the mean annual minimum increased, after 1985 in particular, but these did not take place abruptly enough for them to be regarded as a break in the series. It must be stressed, however, that the increase in minima was then higher than in the mid-1970s and in 1982.

Limited variability in the distribution of moving averages was a distinct feature of the multiannual progression of differences between mean annual maximum and mean annual minimum temperature (Fig. 3). It can therefore be concluded that in the period 1988–1992 all the temperature characteristics in Gaik Brzezowa assumed higher values. This fact can hardly be explained only by the environmental effects of the reservoir, as it coincided with temperature changes of the same nature noted in Kraków and Szymbark (Table 4).

The analysis of the series noted at the base station in Gaik Brzezowa, together with the subperiods 1971–1984 for Terasa and 1982–1992 for Kopiec, needs a comment concerning the trends for air temperature changes in connexion with both the general conditions of atmospheric circulation and the location of the base station in two thoroughly different topographical places in these two subperiods. The analysis of moving averages for temperature calculated for a year and mean extremes (Fig. 4–6) showed that a downward trend was prevailing at Terasa from 1971 to the mid-1980s. Afterwards a considerable increase in all three examined air temperature parameters oc-

TABLE 4. Mean air temperature (t) and standard deviation δ (in °C) for the year, winter and summer on sites in the Raba valley and in Szymbark

Station	Period 1971–1984						Period 1982– 1992						Period 1971–1992					
	Year		Winter		Summer		Year		Winter		Summer		Year		Winter		Summer	
	t	δ	t	δ	t	δ	t	δ	t	δ	t	δ	t	δ	t	δ	t	δ
Gaik Brzezowa (base station)	7.7	0.61	–1.2	1.41	16.3	0.66	8.2	0.88	–0.8	2.14	17.0	1.03	7.9	0.79	–1.0	1.79	16.6	0.93
Zbocze	8.2	0.71	–0.8	1.43	16.8	0.85	8.6	0.84	–0.8	2.27	17.6	1.07	8.3	0.80	–0.9	1.85	17.1	1.04
Szymbark	7.6	0.59	–1.2	1.26	16.2	0.69	7.7	0.69	–1.8	1.90	16.6	0.82	7.6	0.65	–1.5	1.67	16.4	0.78

Gaik Brzezowa base station is represented:
1) by the site Terasa in the period 1971–1984,
2) by the site Kopiec in the period 1982–1992,
3) by the joined series from Terasa and Kopiec sites in the period 1971–1992.

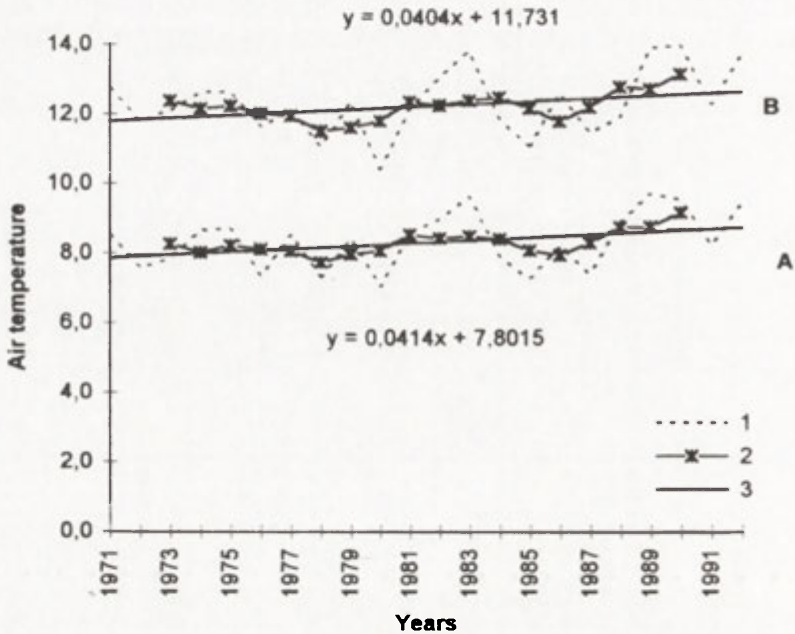

Fig. 2. Mean annual air temperature (A) and mean annual maximum of air temperature (B) at the Zbocze site in the years 1971–1992
1 — mean annual values of air temperature, 2 — moving averages, 3 — line of trend

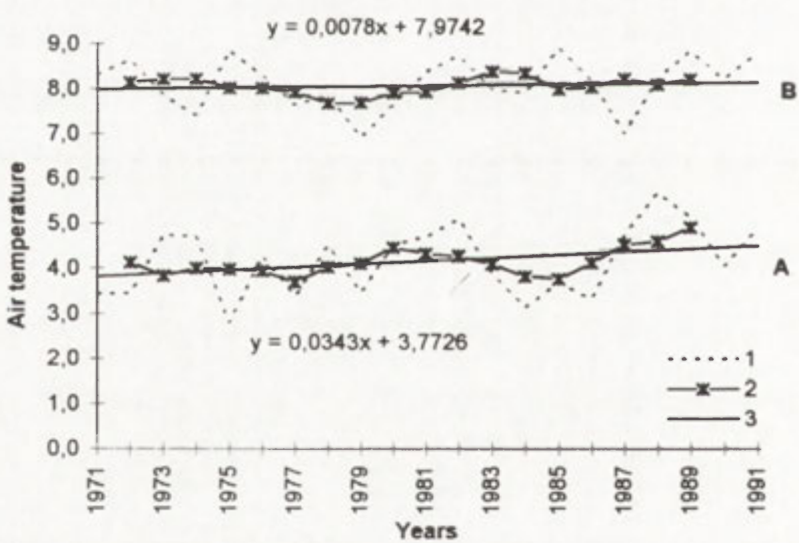

Fig. 3. Mean annual minimum of air temperature (A) and difference between mean annual maxima and minima of air temperature (B) at the Zbocze site in the years 1971–1992. Explanations as in Fig. 2

curred. To a large extent, a decrease in mean annual temperature resulted from a periodic intensification of winter severity. According to K. Piotrowicz (1994), a higher frequency of frost days (t_{max} 0°C) and higher sums of cold were observed in Kraków from 1981 to winter 1986/7. Subsequently (in the years 1988–1992), winter thermal conditions became evidently milder, and the differences in mean monthly air temperature between Kraków and Gaik Brzezowa decreased (Trepińska 1994). This evident warming noted at the turn of the 1980s and 90s resulted from effects of both regional significance (atmospheric circulation) and local significance (operation of the reservoir).

The series noted at Kopiec station in the subperiod 1982–1992 is marked by a change in the trend from negative to positive and by a three to four-fold increase in the values of mean annual air temperature and of mean extremes (Figs.4–6). This series comprises both the very warm winters of the five-year period 1988–1992, which were experienced in the whole of Poland and in large areas of Eurasia, and warm summer periods after 1985. Thus, the construction and operation of the reservoir in the Raba valley coincided with a considerable climatic anomaly whose origin is connected with strongly developed forms of zonal circulation in winter and meridional circulation in midsummer (Kożuchowski 1995). The above facts explain a wide range of changes in mean annual, winter and summer temperatures (Table 4) as well as in respective values for mean extremes in 1982–1992 at Kopiec station, which assumed the role of the base station (Table 5). This is why the coefficients of regression in the series of observations at the base station in Gaik Brzezowa illustrate the nature of the thermal fluctuations taking place in Central Europe. Namely, the period 1971–1984 is characterized by a downard trend in air temperature (Figs. 4, 5, 6), which is documented clearly by mean annual values and mean extreme values. The period 1982–1992 is, on the other hand, characterized by an upward trend. However, it is difficult to estimate qualitatively how the periodic location of the station in a concave topography (Terasa) and in a convex one (Kopiec) affected the magnitude of the trend. Comparison of Figs. 4, 5 and 6 shows that the highest inhomogeneity at the base station was demonstrated by the series for mean minimum annual temperature. The analysis of the magnitude and direction of the trends at Zbocze station in the same subperiods as those under consideration for the base station (Fig. 7, 8 and 9; Table 5) can help in the interpretation of the role of topography and of the reservoir (from 1988) in the formation of the above mentioned trends. The location of the Terasa and Zbocze stations close to each other (difference in altitude 24 m) allows it to be concluded that differences between regression coefficients originate from the effects produced by local topographical conditions. At Terasa, both the examined thermal characteristics demonstrated a downward trend in the years 1971–1982, whereas at Zbocze, located at the upper border of the reservoir of cold air, there were slight upward trends in mean annual temperature and mean minimum temperature, and a slight downward trend in mean maximum temperature. The transfer of the station onto the Foothills

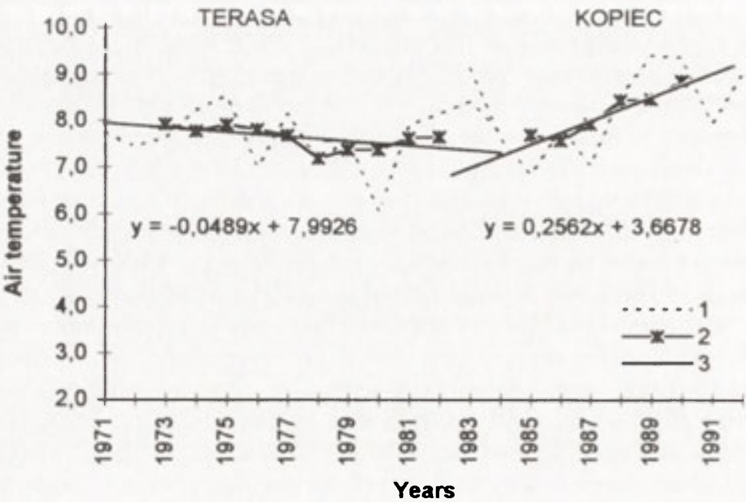

Fig. 4. Mean annual air temperature at Terasa (in the years 1971–1984) and Kopiec (1982–1992). Explanations as in Fig. 2

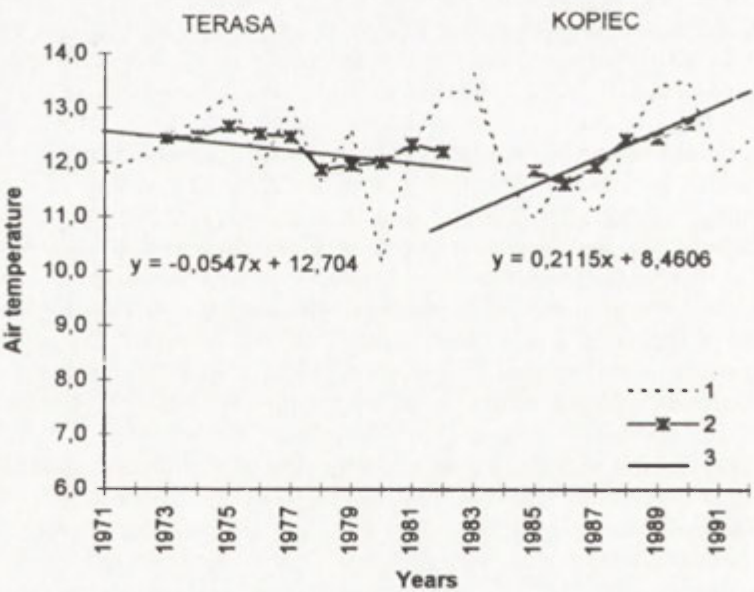

Fig. 5. Mean annual maximum of air temperature at Terasa (in the years 1971–1984) and Kopiec (1982–1992). Explanations as in Fig. 2

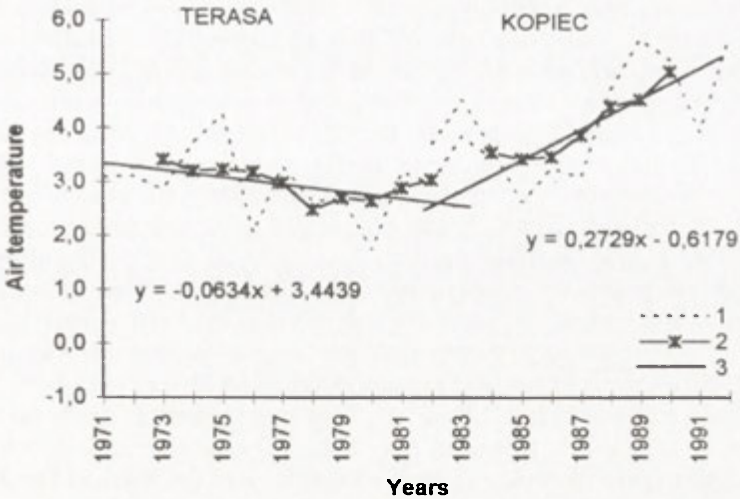

Fig. 6. Mean annual minimum of air temperature at Terasa (in the years 1971–1984) and Kopiec (1982–1992). Explanations as in Fig. 2

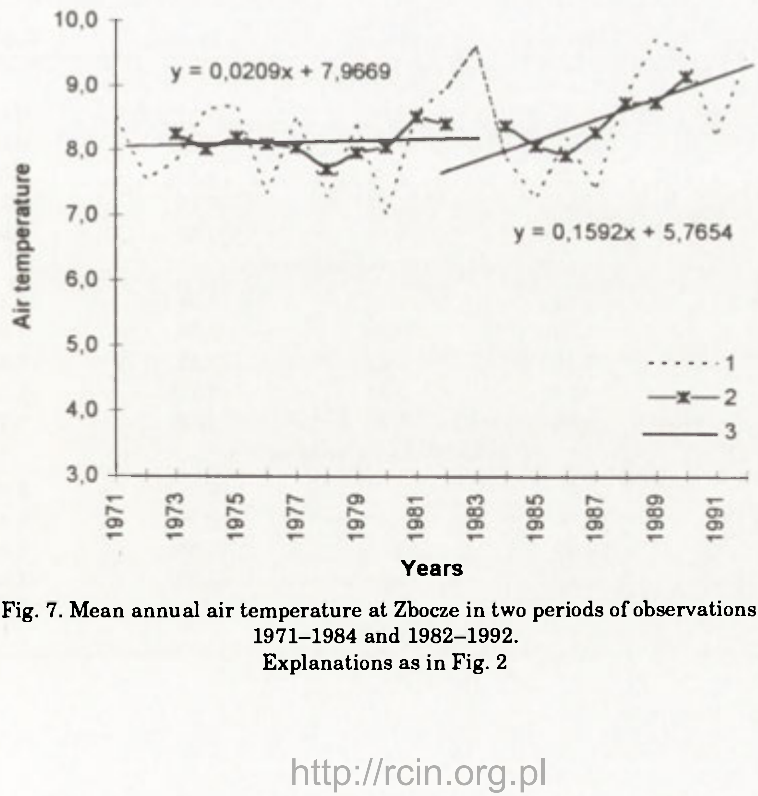

Fig. 7. Mean annual air temperature at Zbocze in two periods of observations: 1971–1984 and 1982–1992. Explanations as in Fig. 2

ridge reduced the difference in altititude between Kopiec and Zbocze to 19 m. As a result of general climatic warming, the coefficients of linear regression in the trend equations assumed positive values, with the means for temperature increase being 1.4 times higher at Kopiec than at Zbocze. These differences were undoubtedly produced by a change in local conditions of the substratum in the area of the Raba valley after 1988. Additional information was provided by a comparison of the magnitude of seasonal trends in air temperature per decade. At the Terasa and Zbocze stations (1971–1984) and at the Kopiec and Zbocze stations (1982–1992), the above comparison revealed agreement in the direction of changes in winter and summer (Table 5). However, in transitional seasons, especially in spring, the direction of changes at the above pairs of stations were sometimes seen to be different. The difference between the data for the periods 1971–1984 and 1982–1992 lay mainly in the increased intensity of changes in mean winter temperature (Tables 4, 5) and corresponding mean extremes at Zbocze (see Figs 7, 8 and 9) as compared to Terasa (Figs 5, 6). This domination of thermal changes at Zbocze was also maintained in summer in the former period, whereas in the latter, the magnitude of the studied trends was greatest at the Foothills ridge.

TABLE 5. Trend values (°C/10 years) for characteristics of air temperature on the sites in the Raba river

Season	Period 1971-1984		Period 1982-1992	
	Terasa	Zbocze	Zbocze	Kopiec
	a) mean temperature			
Winter	–2.32	–1.69	5.51	6.93
Spring	0.02	–0.11	–0.35	0.62
Summer	0.25	1.08	1.36	2.21
Autumn	0.24	1.57	–0.16	0.48
Year	–0.49	0.21	1.59	2.56
	b) mean maximum temperature			
Winter	–2.31	–2.19	5.97	6.73
Spring	0.09	–0.98	0.33	1.30
Summer	0.18	0.81	1.32	1.65
Autumn	0.36	1.46	–1.72	–1.22
Year	–0.55	–0.22	1.47	2.12
	c) mean minimum temperature			
Winter	–2.80	–1.74	5.60	5.90
Spring	–0.04	0.40	–0.58	0.80
Summer	0.29	1.33	1.66	2.46
Autumn	0.23	1.63	0.08	1.75
Year	–0.63	0.41	1.69	2.73

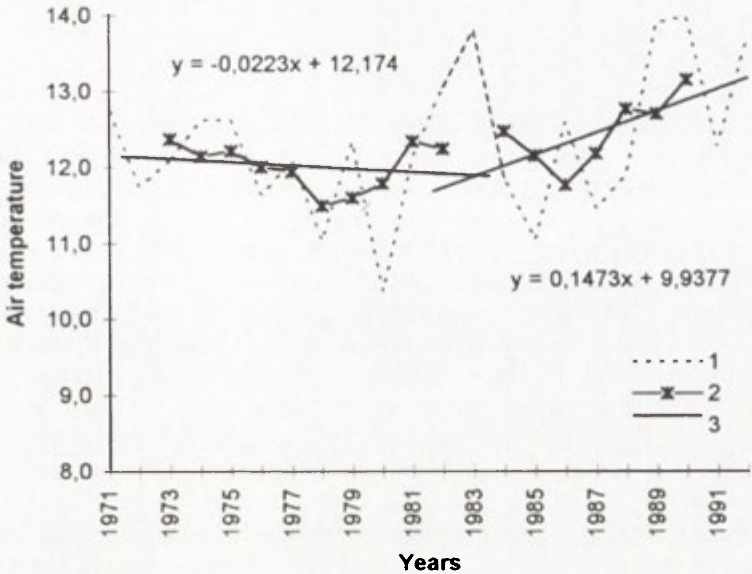

Fig. 8. Mean annual maximum of air temperature at Zbocze in two periods of observations: 1971–1984 and 1982–1992.
Explanations as in Fig. 2

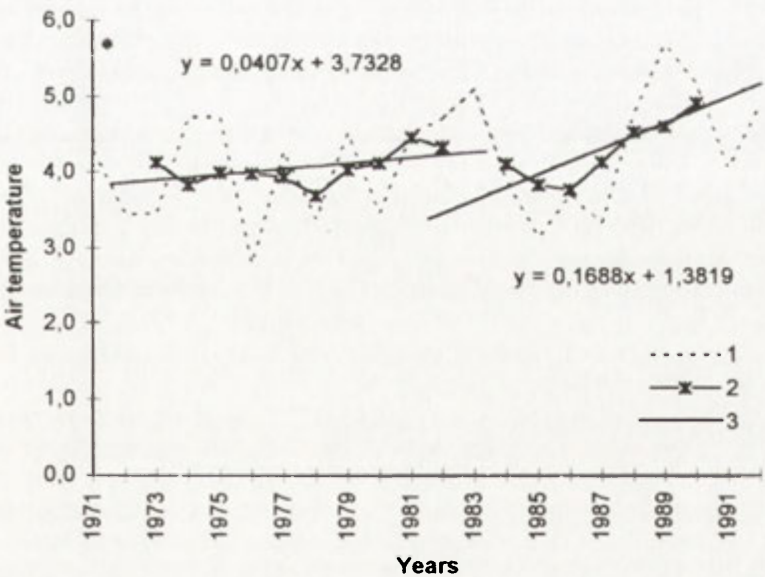

Fig. 9. Mean annual minimum of air temperature at Zbocze in two periods of observations: 1971–1984 and 1982–1992.
Explanation as in Fig. 2

CONCLUSION AND REMARKS

The study on the changes in air thermal conditions was performed in the Foothills area of the Raba River valley over the period 1971–1992. The obtained results prove that a cautious choice of observation stations is required to estimate the effects of climatic warming on the regional scale and to analyse their origin. The study revealed a number of important regularities in the effects of external and internal factors on the local climate over a period of time. The effect of atmospheric circulation, treated as an external factor affecting the structure of climate and its transformations on the regional scale, manifested itself in the occurrence of climatic fluctuations and was recorded in the observation series at all the stations. The period from the mid-1980s was found to have a downward trend in air temperature mainly because of a succession of severe winters. Subsequently, in the period 1982–1992, an unusually strong warming took place as a result of intensified western circulation in winter and meridional circulation in summer. These trends appeared in the whole area of the Carpathian Foothills and in the adjoining Subcarpathian Basin.

Topography and the character of the substratum (including the construction of the reservoir) were classified as internal factors influencing the topoclimate. The climatic fluctuation revealed as climatic warming coincided with the effects of the reservoir on thermal conditions in its closest vicinity. The general circulation effects on changes in the spatial distribution of air temperature in the area of the valley masked to a certain extent the effects of local factors. The above effects together produced air temperature trends of unusually great magnitudes, exceeding even those for corresponding thermal parameters recorded in the centre of Kraków. It should be emphasized here that the series of data from the base station in Gaik Brzezowa (which was moved 43 m higher from Terasa in the bottom of the valley onto the Foothills ridge) did not demonstrate evident signs of a break in homogeneity after application of simple analytical methods to the time series. Only comparison of the magnitude of the trend at the base station in Gaik Brzezowa with those at the stations in Kraków and Szymbark provided evidence for their higher values in the Raba valley.

The analysis of directions and trends to climatic changes performed with the use of linear trends for the same subperiods, chosen on the grounds of facts from the history of the Gaik Brzezowa station, showed that there is a noticeable difference in transformations of thermal conditions between the stations in the area of the valley over the examined period of time. Zbocze station (altitude 283 m) did not change its location in relation to topography, but was located in the direct vicinity of the reservoir after its construction. It showed an upward temperature trend over the whole period 1971–1992. The trend was a little milder than that at the base station. The observation series from the latter consisted of data collected at two different sites in the examined subperiods. Consequently, the transfer of the base station onto the ridge after the construction of the reservoir, led to new relations between the stations regarding the intensity of changes in climatic conditions. In the years 1971–1984, the magnitudes of trends in mean annual and seasonal temperatures and in corresponding extreme temperatures at Zbocze and Terasa were for the most part in agreement with each other as far as the direction of changes goes, but their intensities at Zbocze were several times greater than at Terasa. In the years 1982–1992, the recorded trends provided evidence for a general growing trend towards warming and for its more intense manifestations at the Kopiec station, more exposed to advections of air masses than Zbocze. The latter was more under the influence of local circulation produced by the exchange of energy and the circulation of matter in the vicinity of the reservoir.

The following methodological conclusions can be drawn from the above presentation. The use of trends in studies of the inhomogeneity of observation series appeared to be justified. This method is recommendable when metadata are available, providing information on possible origins of breaks in homogeneity of observation series, as the choice of reference point in relation to which calculations are performed can be decisive for the magnitude and direction of temperature changes.

Estimation of long-term trends to climatic changes in areas of varied topography should be based on such stations which are open sites accessible to advections of fresh air masses, which are of limited influence of internal factors in a climatic system and which represent local environmental conditions and produce local circulation systems (lake breeze, town breeze). Human activity, transforming the system of local climate-forming factors, can produce such changes in thermal conditions in time and space that the determined magnitudes of trends can be overestimated or underestimated in comparison to the actual trends resulting from the course of climatic elements. There also arises a suggestion, requiring further studies, that depending on the location of stations in relation to topography, reservoirs, plant communities and other forms of land-use, the values of trends determined for small areas can differ in magnitude and sign from each other.

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THERMAL CHARACTERIZATION OF WINTERS IN THE 20TH CENTURY IN KRAKÓW

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ABSTRACT: Based on Krakow's measurement series of air temperature in the 20th century an attempt was made to analyse the winter season by means of some criteria which are important for the thermal conditions which — in turn — influence natural processes and phenomena. The first day with mean daily air temperature <0°C was taken to determine the beginning of a winter and the last such day for the end of winter. The characterization of winters was based on the number of winter days (mean daily air temperature <0°C), the number of frosty days (daily maximum air temperature <0°C), the number of extreme frosty days (daily maximum air temperature <–10°C) and the sums of frost (sums of mean daily air temperature <0°C). Special attention was paid to extreme winters because of their thermal conditions as well as their frequency and variability. It was established that recently observed winters are the mildest in our century and that the concentration of such winters in the 1980s allowed for a link with global warming. The winters in question are inducing environmental changes.

KEY WORDS: winters, extreme winters, air temperature, South Poland, Kraków.

INTRODUCTION, AIM OF STUDY

Since the middle of the 19th century the geographical environment has been experiencing increasing human impact connected with intensive urbanization and industrialization. A growing threat to human living conditions has led to increased interest in research into the climate and its changes. As A. Kosiba (1956) states the most distinct indications of climate changes are thermal oscillations in winters which are strongly marked in the mid-latitude zone, including Poland. This is because, of all the seasons, it is winter which shows the largest deviations from the mean many-year values for such characteristics as: the dates of commencement and end, duration and mean temperatures. It is therefore to extremely frosty and warm winters that researchers have long been drawn, with first mentions being found already in medieval chronicles.

The invention of the first meteorological instruments made it possible to analyse not only the extreme winters described by different annalists, but winters in general, thanks to meteorological stations registering climatic elements constantly. Therefore we have many examples of frosty and mild winters in recent centuries, and mention might be made of 1829/30 one of the frostiest winters in Central Europe, which was characterized by long, intense frosts and mean temperatures for December, January and February of –9.6°C in Warszawa (Paczos 1982), and –10.3°C in Kraków. Recently there have been many publications about winters, making reference to their mild conditions. It had been assumed that the global warming occurring in the 20th century reached its maximum in 1938 and lasted until the 1960s when there was considerable cooling (Kożuchowski 1990). However, as Jones and Kelly state, in 1981 an increase in mean air temperature in the Northern Hemisphere was observed again, with the anomaly of 0.5°C, exceeding the former maximum from 1938 (0.43°C) (after Kożuchowski 1990).

Analysing thermal conditions in Kraków M. Hess (1967) showed that there existed a trend towards increased temperature for the winter season over the last two centuries.

In turn, J. Trepińska (1977) studying the mean temperatures of winters in Kraków in the period 1826–1975, stated that mild winters in the 19th century occurred occasionally (21.3%) but were 2.5 times more frequent (54.6%), in the 20th. The frequency of frosty and very frosty winters decreased from 10.7% in the years 1826–1900 to 8.0% in the period 1901–1975.

The literature contains contradictory opinions about the mildest and most frosty winters of the 20th century. This is thus proof of the importance of the main indices defining winter severity. Some authors consider winter 1928/9 to be the most frosty, since it was then that the absolute minimum temperatures for Poland were noted: –40.6°C in Żywiec and –40.4°C in Olkusz (Paczos 1982). As Gumiński (1931) described the extremely low air temperatures had a serious economic impact, killing many animals and plants, disturbing communication, road and railway transportation and freezing the sea ports in Gdynia and Gdańsk on 10th February 1929. However, H. Mitosek (1961) classified this winter as the second most frosty after that of 1939/40, which in his opinion was the most frosty because it had, among other indices, the highest number of frosty days with mean daily temperature below –10°C. This was the first winter of the Second World War and H. Mitosek stated (1961) that in consequence its severity was reflected in neither newspapers' notes, nor in the scientific literature. However interesting data about the damage to orchards in the so-called General Guberniya (German-occupied Poland, 1939–1945) are known. 97% of pear trees, 94% of plum trees and 76% of apple trees were destroyed (Mitosek 1961). Nevertheless, there are still other authors who claim that winter 1962/3 was the most frosty and "the winter of the century". So which winter was in fact the most frosty and which the mildest? Why do some authors consider winter 1928/9 the most frosty while others — 1939/40 or 1962/3? The answer to the second question is surely easy if note is taken of the period taken by different authors as winter and the criteria used to characterize it.

The majority of climatologists take three calendar months (1st December–28th or 29th February) to be winter time (Wiszniewski 1960, Hess 1967, Trepińska 1971). However, in some works winter is distinguished as four (December–March) or five (November–March) (Kosiba 1956, Paczos 1982). According to A. Kosiba (1956) and H. Mitosek (1961) taking only a few calendar months does not show the real character of a winter, because it actually happens very rarely that a winter begins or ends on such a date. Moreover, such an approach fails to consider the complicated and variable character of the Polish climate. This was the reason for introducing the terms "specific winter" (Kosiba 1956) and "real winter" (Mitosek 1961). According to these authors, the beginnings of winters should be the dates after which a significant dominance of days have mean daily temperature below zero. The end occurs when temperatures are above zero (Mitosek 1961). H. Makowiec (1983) does not question the general justness of this proposal but states that "the criterion defined in such a way leaves some margin for free interpretation with a consequence of a probable lack of possibility of comparison of the results obtained by different authors".

Farmers, living closer to meteorological phenomena than people in cities, used to classify winters on the basis of damage caused by frosts to orchards and winter crops. H. Mitosek (1961) states however that the phenomenon is strongly connected with the orography of the area, type of soil, duration and thickness of snow cover and with the direction and speed of the wind. Therefore these are not the results of the negative temperatures, but the temperatures themselves that should be the basis of distinguishing mild and frosty winters. Unfortunately, although there is rich literature considering the thermal conditions of winters there are still no universal methods and criteria for their characterization, typology or classification, though as early as in 1958 A. Kosiba wrote "About the necessity of uniforming international scale of basic thermal criteria in climatology".

The aim of this study is to attempt to characterize the winters of the 20th century in Kraków, as a step towards defining the suitability of thermal criteria in the classification of that season of the year. In looking for the best criteria to define the dates of the beginning and end of winters and their characteristic traits, the author rejected standard indices (e.g. winter as 3 months — Dec.–Feb., mean monthly winter temperature as a basic criterion of characteristic), because it was assumed that recent winters had started in November and had taken an untypical course, requiring an enrichment of the criteria used to better describe that season. In the analysis, special attention was paid to the winters which depart in their thermal conditions, from the mean values in this century.

Kraków is one of the few cities in Poland and Europe that possess a continuous multi-year series of meteorological measurements and has also been shown to represent Central Europe, as secular synchronity was found between air temperature changes in Kraków and those in Wrocław, Prague, Vienna, Stockholm, Vilnius, Kiev and other cities (Trepińska 1971, 1976, 1977). In addition K. Marciniak et al. (1986) in a work about the spatial differentiation of thermal anomalies in Europe included Kraków to the area lying evenly with a parallel of latitude in Europe and characterized by coherent changes of the January temperature. The data from that station reflect changes caused by natural climatological factors and urbanization, the effects of which are thought to be responsible for the global warming of recent years.

SOURCE MATERIALS AND METHODS

The data used in the analysis were: daily values for air temperature (mean and maximum) from the period 1901/2– 1993/4 from the Climatological Station of the Department of Climatology, Institute of Geography, Jagellonian University in Kraków (φ = 50°04'N, λ = 19°58'E, h = 220 m a.s.l). The station is at the lower margin of the moderately warm vertical climatic zone in the Carpathians in the range of the climate of basins (Hess 1965).

From the methodological point of view the main problem of this study was to state the beginning and end of winter time, as the term "thermal winter", used in the literature is interpreted differently by many authors as was shown in the "Introduction" section. The decision was therefore made to define the season explicitly, taking as its beginning the first day when mean daily air temperature was below 0°C and for its end the last such day. The following indices were used in the characterization of thermal conditions:

1) the number of winter days (t_{mean}<0°C),

2) the number of frosty days (t_{max}<0°C),

3) the number of days with severe frost (t_{max}<–10°C),

4) the sum of frost, i.e. the sum of mean daily air temperatures below 0°C (Σt_{mean}<0°C).

According to the author (Piotrowicz 1994a) these criteria are sufficient to define the degree of winter severity because:

— days with t_{mean}<0°C are characteristic for the winter period. In climatology mean daily temperature has long been accepted as a criterion distinguishing the limits of the thermal seasons of the year, and it also gives — according to H. Mitosek (1961) — a better characterization of thermal conditions during the whole 24-hour period than the indications of maximum and minimum thermometers, which reflect only the temperature of a short period, often only a moment,

— days with t_{max}<0°C are (according to Kosiba 1956) an indicator of the lower limit of potential conditions for snow thawing and the continuity of negative temperatures during the day-time, which is much more important from the point of view of bioclimatic and economical conditions than night-time,

— days with t_{max}<–10°C do not appear every winter in Krakow and this criterion therefore helps to better characterize very frosty winters,

— sum of frost — a strict quantitative criterion characterizing thermal conditions is used by many climatologists (e.g. Hess 1965, Paczos 1982) and very well reflects the severity of winter.

After analysing every winter from the 93 taken into consideration, more careful characterization was confined to those for which dates of beginnings and ends and values for other criteria were lower than the lower decile and higher than the upper decile. As P.R. Crowe (1987) states, 10% of all cases from the beginning and end of an arranged distributive sequence defined in this way make "mean extremal values" and those are usually the values showing "natural capriciousness", i.e. being abnormal.

BEGINNINGS AND ENDS OF WINTERS

In the 20th century in Kraków winters used to begin in the middle and last third of November, and end in the middle and last third of March (Figs. 1, 2). However there were winters which had already started in October or were delayed until December and also ones that ended in January or April. Therefore, following this criterion extreme winters should be starting before 28th October (early winters) or after 8th December (late ones) and those which ended before 24th February (early ending winters) and after 7th April (late ending winters).

Examples of such winters are shown in Table 1 where first most extreme winters were gathered. The winter that started earliest was that of 1908/9 (19th Oct.), and the latest — 1902/3 (19th April). In the studied period there were two winters which may be classified early but ending late (1912/3 and 1940/1) and one that was early but ending early (1926/7). It is very interesting that four of the early-ending winters occurred in the late 1980s and early 1990s.

TABLE 1. Extreme winters in Kraków in the years 1901/2–1993/4 according to dates of their beginnings and ends

Winters							
Early		Late		Early ending		Late ending	
1908/9	19.X	1929/30	18.XII	**1989/90**	9.II	1902/3	19.IV
1920/1	21.X	1970/1	18.XII	**1988/89**	29.II	1954/5	18.IV
1946/7	24.X	1992/3	16.XII	1966/67	17.II	1911/2	13.IV
1922/3	25.X	1949/50	13.XII	**1990/91**	20.II	1912/3	13.IV
1926/7	25.X	1972/3	13.XII	1933/34	21.II	1927/8	13.IV
1947/8	25.X	1951/2	12.XII	1919/20	22.II	1985/6	12.IV
1912/3	26.X	1960/1	12.XII	1926/27	23.II	1940/1	10.IV
1979/80	26.X	1903/4	11.XII	1935/36	23.II	1904/5	8.IV
1940/1	27.X	1974/5	9.XII	**1993/94**	23.II	1910/1	8.IV

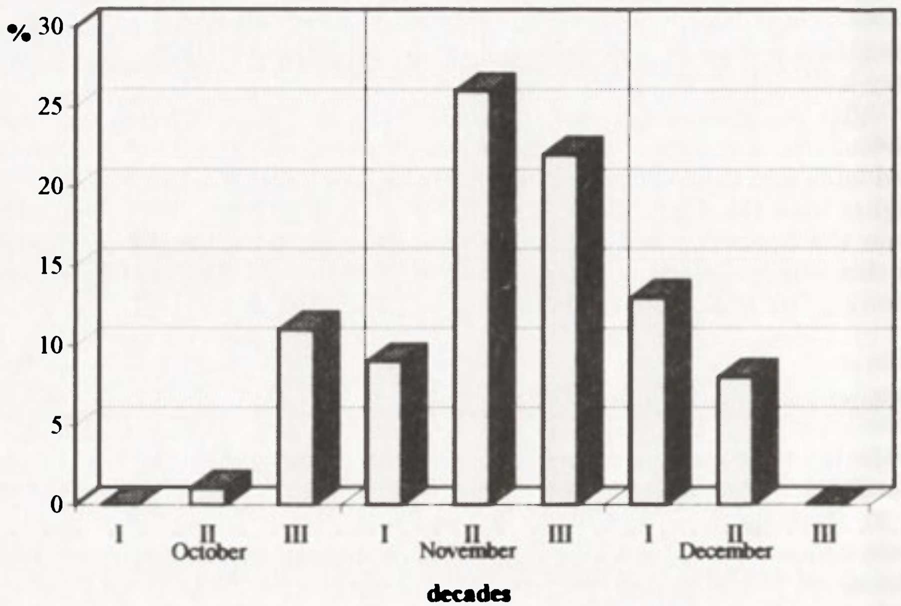


Fig. 1. Beginnings of winters in the years 1901/2–1993/4

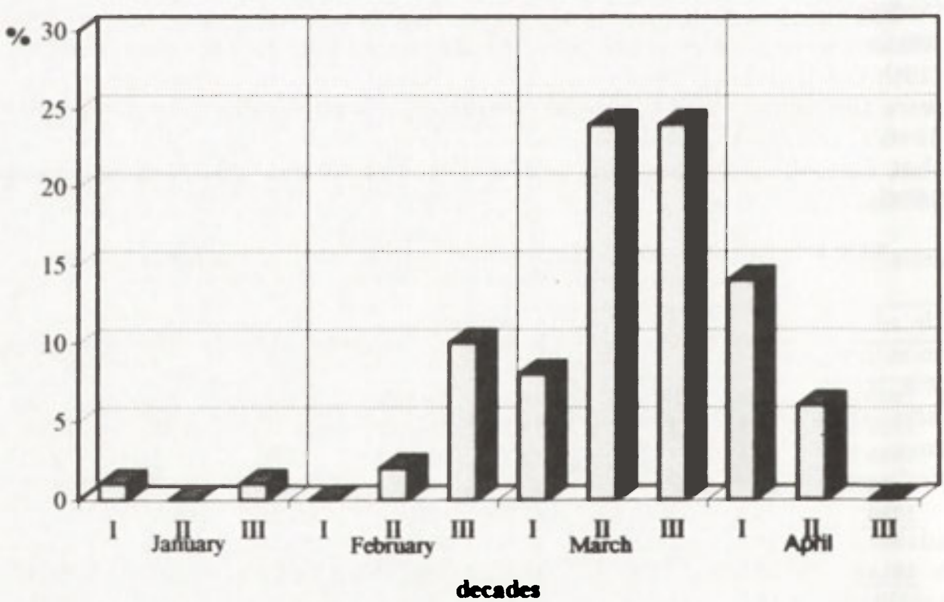
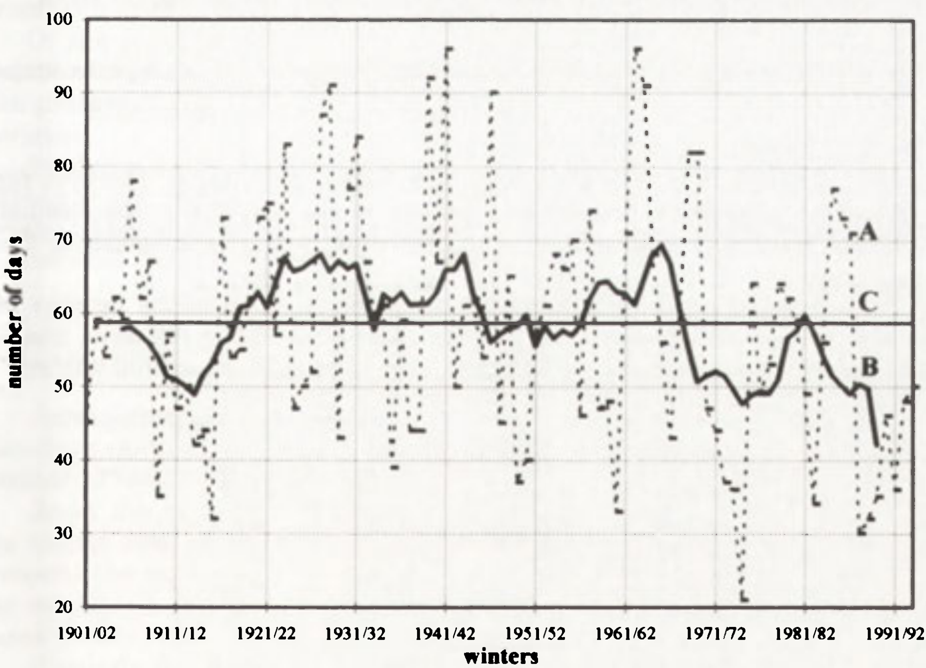


Fig. 2. Ends of winters in the years 1901/2–1993/4

THERMAL CHARACTERIZATION OF THE WINTERS

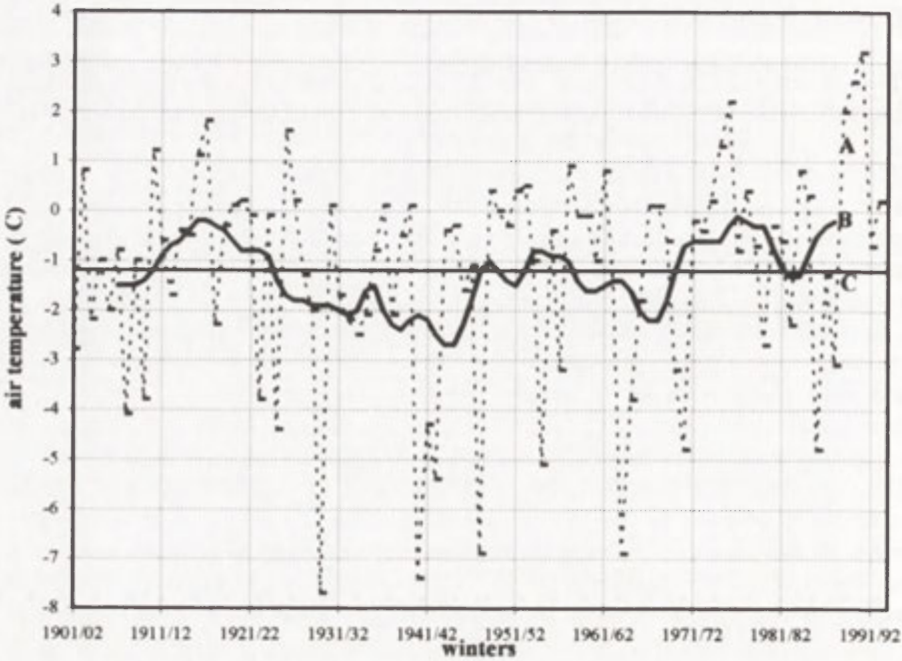
The occurrence of days with mean daily air temperatures below 0°C is a characteristic trait of the cold half-year in our climate, and these days are,therefore, named winter days.

The analysed data from the period 1901/2–1993/4 allow it to be stated that an average winter has 58.6 days with t_{mean}<0°C. The value varied from 97 days in 1908/9 to 21 days in 1974/5 (Fig. 3). On the basis of the mean number of winter days in the studied period and the 10-year running average a trend towards changes in these days can be seen. As is shown in Fig. 3, the first two 20-year periods of the 20th century had numbers of winter days lower than the many-year mean. From the 1920s to the 1960s there was a cold spell, with an increased number of days with t_{mean}<0°C, albeit with a break in the years 1947–1957 when the frequency of such days was close to the multi-year mean. Noticeable from the 1970s is a distinct warm spell which has lasted until today with a short cold spell in the mid 1980s. This trend is similar to the one presented in the literature and most often defined on the basis of the mean temperature of the three winter months (Dec.–Feb.) (Fig. 4). The increase in that temperature is accompanied by a decrease in the number of winter days, and the thermal periods of winter



A – number of winter days **B** – 10-year running average **C** – multi-year average

Fig. 3. Number of winter days in the years 1901/2–1993/4



A – number of winter days **B** – 10-year running average **C** – multi-year average

Fig. 4. Mean air temperature in winter (Dec.–Feb.) in the years 1901/2–1993/4

severity distinguished with the use of both indices are similar. However for a detailed characterisation of the winter period the criterion of the number of winter days seems to be better as it considers the real length of the winter period and not only the standard one.

Table 2 shows extreme winters following the criterion of the number of days with $t_{mean}<0^{o}C$ higher than the value of higher decile (83 days, frosty winters) and lower than the value of the lower decile (36 days, mild winters).

TABLE 2. The most severe and mildest winters in Kraków in the years 1901/2–1993/4 according to numbers of winter days ($t_{mean}<0^{o}C$)

Most severe	$t_{mean}<0^{o}C$	mildest	$t_{mean}<0^{o}C$
1908/09	97	1974/75	21
1941/42	96	1993/94	30
1962/63	96	1987/88	30
1939/40	92	1988/89	32
1928/29	91	1915/16	33
1963/64	91	1960/61	33
1946/47	90	1982/83	34
1927/28	87	1989/90	35
1931/32	84	1909/10	35

FROSTY WINTERS

As Table 2 shows the 20th century winters classified as the most frosty according to different criteria and authors are: in fifth place — 1928/9; in fourth and second place winters from the years of the Second World War (1939/40 and 1941/2) and in third place the so-called "winter of the century" (1962/3). Unexpectedly, winter 1908/9 takes first place in the table. This is possible thanks to this being an early winter, with the first day with mean daily air temperature below 0°C occurring as early as on 19th Oct. (see section "The beginnings and ends of winters"). Winter 1946/7 can also be classified as early and frosty.

The evaluation of winter severity on the basis of one criterion is insufficient, as the author states; so applied in addition to better characterize frosty winters was the number of frosty days (t_{max}<0°C), the number of days with severe frost (t_{max}<–10°C) and the sum of frost (Σt_{mean}<0°C). Mean values of these criteria calculated for 93 winters were: 34.6 for the number of frosty days; 2.6 for the number of days with severe frost and –268.1°C for the sum of frost. In extreme winters the values of these criteria change respectively: from 2 (1974/5) to 71 (1928/9 and 1939/40), from 0 (45% of winters in the studied period) to 18 (1939/40) for the number of days with severe frost and from — 33.8°C (1974/5) to –771.2°C (1939/40) for the sum of frost.

Of the most frosty winters mentioned in Table 2 only five reached the values of the other three criteria higher than the upper decile. Those winters are presented in Table 3 together with the values of the mentioned characteristics.

Studying the order of winters arranged according to the described criteria (Table 3) it is difficult to state explicitly which in this century was the most frosty . The important thing is that among them are winters often omitted in detailed climatological analyses (e.g. 1908/9, 1946/7).

MILD WINTERS

Among the mild winters shown in Table 3 the most frequent are those finishing early. These are 1988/9, 1989/90 and 1993/4. In contrast, the mildest winter 1974/5, with the least number of days with t_{mean}<0°C is a late winter.

As in the case of frosty winters the order of mild winters was studied by taking into account the criteria of t_{max}<0°C and Σt_{mean}<0°C. For obvious reasons the number of days with severe frost was not analysed, because — as mentioned while describing source materials and methods — this can be used exclusively to characterize very frosty winters.

Similarly in this case only five of the mild winters from Table 2 reached values of the other criteria lower than the lower decile. As Table 4 shows winter 1974/5 is mildest no matter what criterion is used.

TABLE 3. The most severe winters in the 20th century in Krakow, the numbers of days with frost (t_{max}<0°C), or severe frost (t_{max}<–10°C) and the sums of frost (Σt_{mean}<0°C)

t_{max}<0°C		t_{max}<–10°C		Σt_{mean}<0°C	
1928/29	71	1939/40	18	1939/40	–771,2
1939/40	71	1941/42	16	1928/29	–763,9
1946/47	70	1962/63	14	1946/47	–693,7
1941/42	68	1928/29	12	1962/63	–683,2
1962/63	67	1946/47	10	1941/42	–671,1

TABLE 4. The mildest winters in the 20th century in Krakow, their numbers of days with frost (t_{max}<0°C) and the sums of frost (Σt_{mean}<0°C)

t_{max}<0°C		Σt_{mean}<0°C	
1974/75	2	1974/75	–33,8
1988/89	8	1987/88	–64,7
1982/83	8	1982/83	–68,0
1987/88	10	1988/89	–74,4
1909/10	16	1909/10	–92,6

As mentioned in the "Introduction" section, the climatological literature makes most frequent use of mean air temperature from the 3 winter months (Dec.–Feb.) to analyse changes in winters' thermal conditions. In the 20th century this index varied in Krakow from –7.7°C (1928/9) to 3.2°C (1989/90). H. Lorenc and M. Suwalska-Bogucka (1995) defined the trends of thermal winters in Poland on the basis of the standard deviation of the mentioned values and stated that the mildest winters in Krakow were: 1974/5, 1988/9, 1989/90 and 1993/4, and the most frosty — 1928/9, 1939/40, 1946/7 and 1962/3. The winters classified by the authors as the most frosty are the same as those presented in this paper, while the mildest show concordance only under the first criterion (number of winter days). More detailed analysis (based on the number of frosty days and the sum of frost) showed that only two winters: 1974/5 and 1988/9 can be considered the mildest in both studies. This is of course connected with the different criteria used in the analyses, however detailed studies of the winters in the 1980s, performed by the present author (Piotrowicz 1994b) suggest that mild, atypical winters have appeared recently but mainly as a result of their very early end (in January and February) and a beginning in November. It would probably therefore be useful to include mean air temperature in November into analyses of winters, especially during recent years, as the value can be lower than the one for December.

CONCLUSIONS

The present paper describes the thermal conditions of winters by use of mean and maximum daily values of air temperature, for Krakow's measurement series as an example, for winters 1901/2–1993/4. For the beginning of winters the first day with mean daily air temperature <0°C was taken and for the end of winter — the last such day. To determine winters of an extreme character the author analyzed the cumulative frequency distribution of some thermal parameters and calculated values for the lower and upper deciles of the particular applied criteria. The whole characterisation was based on the number of winter days, the numbers of frosty days, days with severe frost and sums of frost.

The analysis of winters of the 20th century leads to the following conclusions:

1) winters usually began in the second or third decade of November;

2) the end of winters was more variable, occurring between 9th January and 19th April. 53% of winters ended in the middle and last thirds of March;

3) the analysis of the dates of the beginnings and ends of winters carried out in the present paper indicates that the standard winter time should be widened;

4) among the 9 extreme winters (with the dates of their ends before 24th February) 4 were from the late 1980s and early 1990s;

5) the mean values of the thermal criteria used in this paper, calculated from ninety winters were:

— the number of winter days — 58.6;

— the number of frosty days — 34.6;

— the number of days with severe frost — 2.6;

— the sums of frost — (–268.1)°C.

For winters extreme according to thermal conditions the values of the criteria used vary:

— from 21 (1974/5) to 97 (1908/09) for the number of winter days,

— from 2 (1974/5) to 71 (1928/9, 1939/40) for the number of frosty days,

— from 0 (44% of all winters) to 18 (1939/40) for the number days with severe frost,

— from –33,8°C (1974/75) to –771,2°C (1939/40) for the sums of frost.

6) Among the 5 most severe winters defined according to 4 criteria from among the 93 winters in the discussed period there is no big differentiation, making it difficult to designate the most severe one of all;

7) in the group of the 5 mildest winters that of 1974/5 takes first place in the ranking of all criteria,

8) in 1980s there were 3 atypical winters characterized by high temperatures. These were: 1982/3, 1987/8 and 1988/9,

9) the analysis of the thermal conditions of winters confirmed the author's opinion that the degree of the season's severity should be defined on the basis of criteria complementary to each other, because they define the intensity of cold differently.

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VARIATION OF THE TOTAL HYDROCARBON (THC) CONCENTRATION IN THE AIR OVER THE EASTERN PART OF THE GDAŃSK AGGLOMERATION[1]

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ABSTRACT: The paper presents the results of a study on the effects of meteorological conditions on the total hydrocarbon concentrations (THC) in the atmosphere where THC denotes the sum of methane and non-methane hydrocarbons. The testing area was contained within the limits of the Gdańsk Refinery located in the eastern part of Gdańsk in the coastal zone of the southern Baltic Sea (Fig. 1). The experimental data were collected by the Automatic Air Monitoring System of Gdańsk Refinery, and meteorological parameters were measured at Gdańsk–Świbno synoptic station in a period of 351 days. The data were evaluated with the aim of revealing spatial differentiation in THC concentrations in summer and winter (warm and cold seasons) and over the year, as well as to determine the frequency of the average daily concentration classes at particular measurement points under specific meteorological conditions. Meteorological situations influencing THC concentrations were defined and statistical analysis yielded a quality classification of the atmosphere around the Gdańsk Refinery.

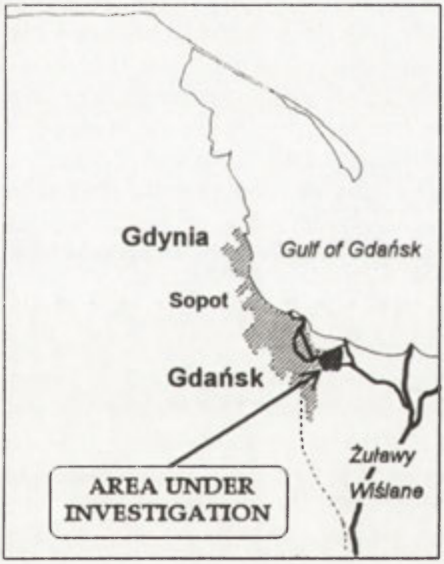

Fig.1. Location of the area under investigation

KEY WORDS: anthropoclimate, air pollution, hydrocarbons, THC concentration around Gdańsk Refinery.

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INTRODUCTION

Hydrocarbons are among the major greenhouse gases. They are emitted to the atmosphere from both natural and anthropogenic sources. Methane is the main component of the hydrocarbon mixture in the case of natural sources, originating from anaerobic decomposition processes of organic matter. The most important anthropogenic emitters of methane in the testing area are chemical plants, especially refineries and automobiles, on one hand, and agricultural activities (methane released as a metabolite in ruminant livestock) on the other.

The THC concentration in the air around the Gdańsk Refinery is a resultant of all the described sources. However, on the yearly basis, the dominant contribution comes from anthropogenic sources, mainly from the production, storage and distribution of oil products in the Refinery. A relatively high emission is also attributed to the Oil Pipeline Exploitation Enterprise (Przedsiębiorstwo Eksploatacji Rurociągów Naftowych — PERN), situated in the immediate vicinity of the Refinery, and to the nearby "Wschód" Municipal Sewage Treatment Plant.

Hydrocarbons are also emitted from the numerous cars on the busy Gdańsk–Warszawa route, which crosses the south–western part of the testing area. Quite a voluminous emission has also to result from the processes of putrefaction ongoing in the waterlogged soil of the Żuławy Wiślane area and the intensive cattle factory farming in neighbourhood farms. The location of the testing area with marked emission sources and measurement points is illustrated in Fig. 2.

Chemical analyzers installed in the measurement network recorded the total sum of hydrocarbons (THC), thus the differentiation of pollution sources by the evaluation of methane coming mainly from natural sources and agriculture was not possible.

The spatial distribution of THC concentrations in the atmosphere over the eastern part of the Gdańsk agglomeration is influenced by the location of emission sources, and their efficiency on the meteorological situation which in turn affects the magnitude and distribution pattern of emissions. The determination of meteorological situations influencing THC concentrations around the refinery plant formed one of the major aims of the present study. Moreover, the results of the investigation sought to answer the following questions concerning:

— the form of annual spatial fluctuations of THC concentrations around the Gdańsk Refinery,

— the effect of particular meteorological elements on THC concentrations,

— the range of air quality disturbance by the Gdańsk Refinery, regarding THC concentrations.

Aerosanitary classification of the atmosphere around the Gdańsk Refinery Plant in relation to pollution by THC was proposed as an additional aim of the study.

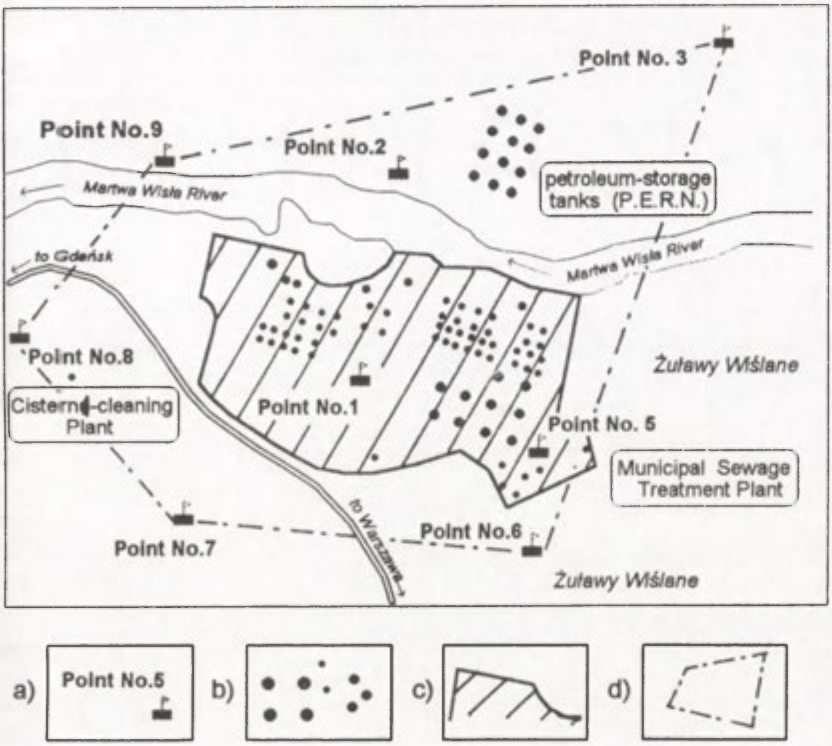

Fig.2. The Gdańsk Refinery Air Monitoring System and location of THC emission sources: a — measurement points, b — anthropogenic hydrocarbon sources, c — boundary of Gdańsk Refinery, d — boundary of testing area

MATERIAL AND METHODS

The investigation was based on the average daily concentrations of THC measured at 8 measurement points of the Automatic Air Monitoring System operated by the Gdańsk Refinery, as well as average daily values of meteorological elements taken at the nearby synoptical station in Gdańsk–Świbno. The air monitoring stations were equipped with chemical analyzers of the Beckman 400 type, which recorded THC concentrations in real time, in the on line mode. The measurement network was computercontrolled with automatic data aquisition.

The experimental period lasted from 06.07.1979 to 31.07.1980. The influence of the following meteorological elements was studied: wind velocity and direction, atmospheric pressure, air temperature, relative humidity, cloudiness, precipitation and fog. The effect of particular elements on THC concentrations was examined in relation to classes defined prior to the analysis. The classification threshold values regarding the meteorological elements

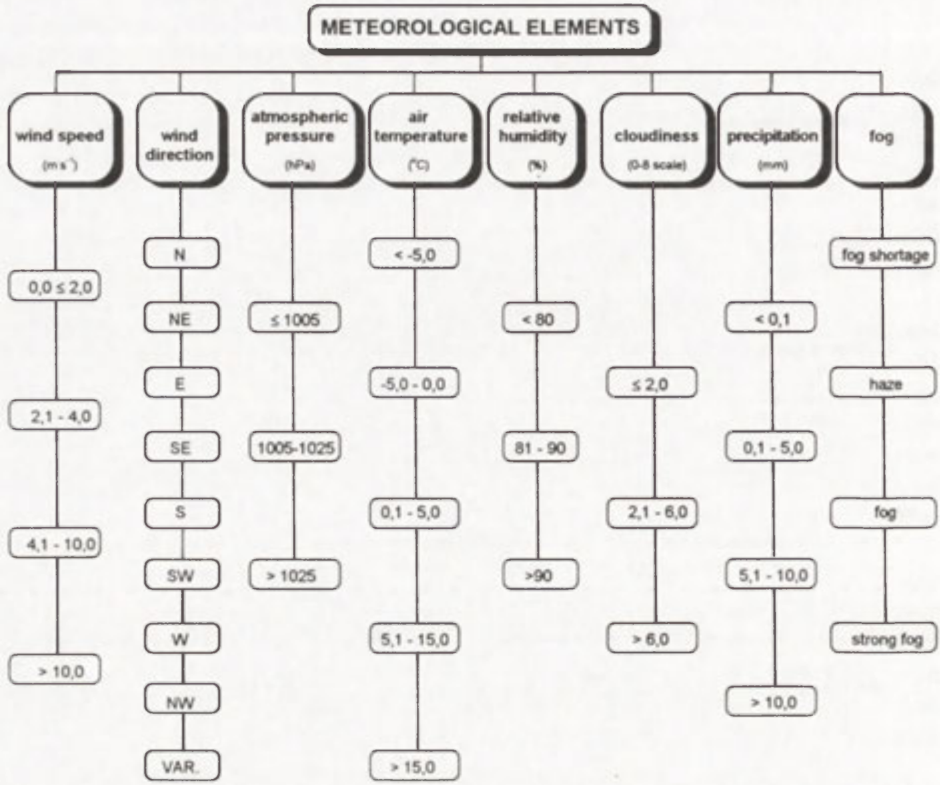

Fig.3. Classes of meteorological elements taken into consideration in investigations

are shown in Fig.3. The evaluation was conducted in three time spans: "summer", i.e. the summer half-year (16.04–15.10), "winter", i.e. the winter half-year (16.10–15.04) and the whole year.

Such analysis concerned both the entire area under investigation with the boundary determined by the line connecting measurement points: 3, 6, 7, 8 and 9 (Fig. 2), and measurement point No 1, located in the centre of the Refinery area, and surrounded by hydrocarbon emission sources.

The influence of meteorological elements on THC concentrations was evaluated by statistical measures like: average and extreme concentration values, range of variability, standard deviation, coefficient of variability, horizontal concentration gradient and correlation coefficient. Since the maximal THC concentrations in the whole measurement period were recorded at measurement point No 1 and the minimal ones at point No 9, the horizontal gradient was calculated as the ratio of the concentration difference between these points to the distance between them. One-way analysis of variance was also applied as a tool to evaluate the relation between THC concentration and meteorological situations.

RESULTS

The average spatial hydrocarbon differentiation patterns, determined in the entire experimental period, were significantly similar regardless of the meteorological conditions. Characteristically, the maximal THC concentrations were recorded in the centre of the Refinery area and gradually diminished towards the boundary. In winter the average, maximal and minimal THC concentrations reached a higher level (Fig. 4, Tab. 1).

TABLE 1. Selected THC concentration properities at measurement points of Gdańsk Refinery Air Monitoring System (6.07.79–31.07.80)

	Measurement points							
	No 1	No 2	No 3	No 5	No 6	No 7	No 8	No 9
	Summer half-year							
average	726	539	231	591	286	235	263	209
maximum	1640	1159	507	991	786	558	439	384
minimum	97	67	10	382	52	64	60	74
range of variability	1543	1092	497	609	734	494	79	310
standard deviation	348	397	158	205	187	139	96	107
	Winter half-year							
average	1306	446	410	772	445	405	337	318
maximum	4450	799	675	1384	771	701	596	492
minimum	289	161	135	299	125	119	106	168
range of variability	4161	638	540	1085	646	582	490	324
standard deviation	1439	177	208	406	302	216	141	98
	Year							
average	1022	492	322	684	367	322	301	265
maximum	2001	963	599	1179	755	635	525	443
minimum	202	118	78	314	92	94	85	125
range of variability	4353	1092	665	1085	1034	637	536	418
standard deviation	1094	308	205	336	264	201	125	116

Source: Wyszkowski, 1994.

A much better evaluation is presented by the frequency of occurrence of concentration classes. The annual range of THC concentrations (0–4450 $\mu g \cdot m^{-3}$) was divided into 11 classes. The histograms illustrating the frequencies of their occurrence are shown in Fig. 5.

Clearly-marked differences in THC distribution patterns were observed between particular measurement points. Among the 8 points of the monitoring network, the full range of THC concentration classes was observed only at measurement point No 1. The analysis showed at this point a significant contribution (10.0%) of the class of maximal concentrations on the one hand, and a minimal contribution of the three least concentration classes (5.7%). A similar frequency distribution was found at point No 5, situated on the grounds of the Refinery Sewage Treatment Plant, with a meagre contribution

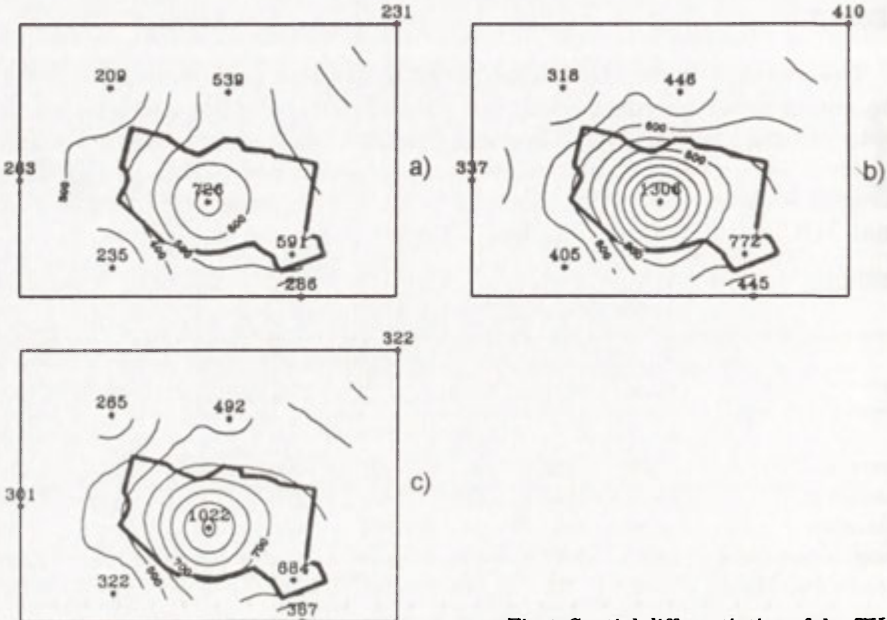

Fig.4. Spatial differentiation of the THC concentration around Gdansk Refinery:
a — summer half-year,
b — winter half-year, c — year

(3.7%) from the three least concentration classes and a remarkable absence of the lowest range of concentrations (< 100 $\mu g \cdot m^{-3}$). This feature was exclusively reserved for this measurement point. Another singular feature, noticed at point No 5, was the fact that nearly 43% of results fell into just one class of concentrations (501–1000 $\mu g \cdot m^{-3}$). The highest frequency was found in the case of the 401–1500 $\mu g \cdot m^{-3}$ concentration range, similarly to measurement point No 1. A significantly different distribution of THC concentrations classes was observed at measurement point No 3. Hardly any dominant concentration class could be distinguished there; with the difference between the highest and lowest of frequency classes only slightly over 7%. Measurement points 7, 8 and 9 showed concentration distribution patterns that were much alike. The THC concentration at these points practically did not exceed 750 g/m^3, and the class 201–400 $\mu g \cdot m^{-3}$ was the one noted most frequently.

In the first approach to determine the meteorological situations affecting THC concentrations, the influence of particular meteorological elements was examined by correlation analysis. The statistical evaluation was conducted with average daily THC concentrations, for the entire testing area and separately with measurement point No 1, for the winter and summer half-years. The results of the calculations are listed in Table 2. Correlation coefficients statistically significant at the 95% confidence level are printed in bold and underlined, while the coefficients approximating significant values are printed in bold.

TABLE 2. Correlation coefficients between meteorological elements and THC concentration around Gdańsk Refinery (GR) and measurement point No 1 (1979–1980)

Meteorological elements	Summer half-year		Winter half-year	
	GR	point No.1	GR	point No.1
wind speed	**–0.135**	–0.119	**–0.139**	–0.073
wind direction	**–0.203**	**–0.275**	–0.098	–0.040
air temperature	**0.193**	**0.162**	**0.318**	**0.325**
relative humidity	–0.112	**–0.168**	–0.042	–0.042
cloudiness	**–0.167**	**–0.246**	–0.017	0.045
atmospheric pressure	**0.144**	**0.224**	0.061	–0.005
precipitation	**0.126**	0.090	0.079	0.110
fog	0.063	0.059	–0.098	**–0.136**

Source: Wyszkowski, 1994.

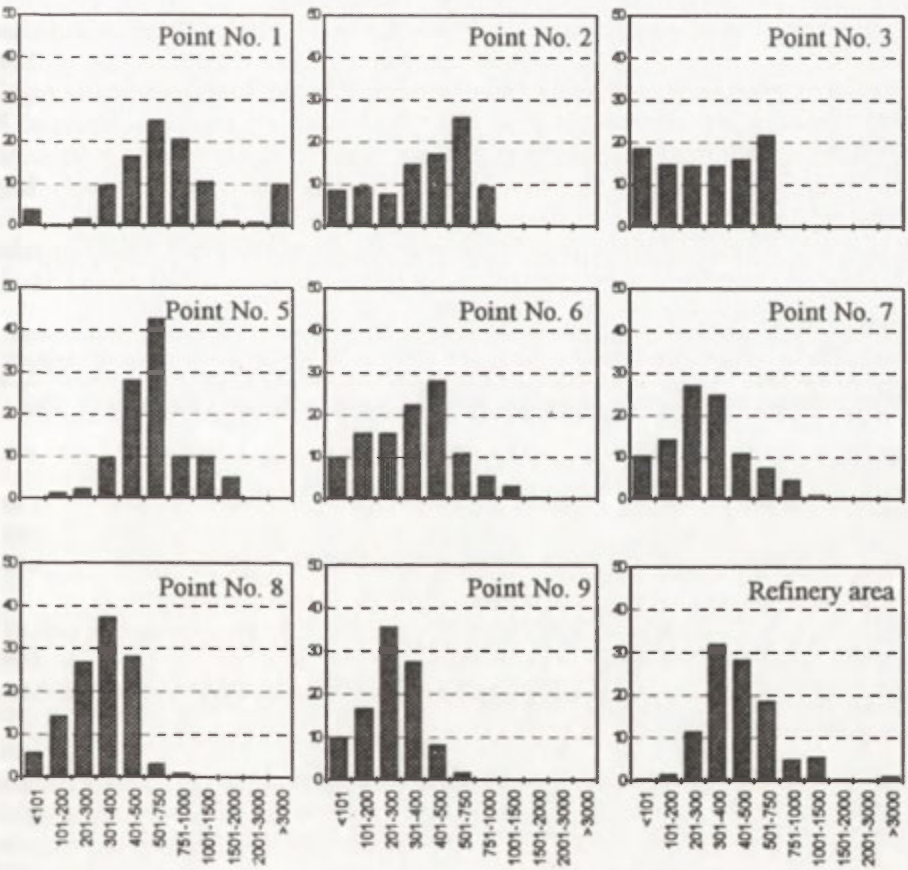

Fig.5. Frequency (%) of average diurnal THC concentration classes at measurement points of Gdańsk Refinery Air Monitoring System for the period 6.07.79–31.07.80

The presented results clearly indicate that there was a much stronger correlation between hydrocarbon concentrations and meteorological elements in summer than in winter. In winter, air temperature turned out to be the most effective element as regards the entire testing area and measurement point No 1. In summer, a significant correlation was found between THC concentrations over the entire testing area and wind direction, air temperature and cloudiness. In the case of measurement point No 1, a significant correlation in summer was found between THC concentration and wind direction, air temperature, relative humidity and atmospheric pressure. Relatively high, positive values of the correlation coefficient regarding air temperature seem to give evidence for the effect of temperature on hydrocarbon emission from natural and anthropogenic sources and consequently on the level of their concentration in the atmosphere. And since in summer relative humidity and cloudiness are directly related to air temperature, the significance of their correlation coefficient values is not surprising.

In summer, the significant correlation between THC concentrations and wind direction can be explained by methane (a main component of THC over the testing area), inflowing from the waterlogged Żuławy Wiślane region (as a result of putrefaction processes). This observation was supported by the presence of high THC concentrations measured in situations with winds from the SE direction, i.e. from the Żuławy Wiślane. The relatively high value of the correlation coefficient with regard to atmospheric precipitation in summer ought to be interpreted cautiously, because of the small number of rainy days and low total precipitation values in the period of the study.

TABLE 3. The influence of selected meteorological elements on THC concentration around Gdańsk Refinery (GR) and at measurement point No 1 (p.1) — results of analysis of variance

	Wind speed	Wind direction	Air temp.	Atmosph. pressure	Relative humidity	Cloudiness	Precipitation	Fog
				Summer half-year				
$F_{(GR)}$	0.82	**2.67**	**4.84**	0.02	1.16	2.07	1.24	2.39
$F_{(p.1)}$	0.66	4.87	3.49	1.44	2.38	4.66	1.44	1.22
F_0	2.66	1.71	2.43	3.06	3.06	3.06	2.66	2.66
				Winter half-year				
$F_{(GR)}$	1.24	1.48	**9.61**	0.14	1.22	0.77	0.08	0.81
$F_{(p.1)}$	1.44	0.95	**8.12**	0.16	1.78	0.19	0.71	1.78
F_0	2.66	1.71	2.43	3.06	3.06	3.06	2.66	2.66

Source: Wyszkowski, 1994.

Although the experimental variables are correlated they still might not be interdependent. The strength of the interaction between particular meteorological elements (for every class) and THC concentration was examined by the one-way analysis of variance method. The analysis of variance was conducted separately for the summer and winter half-years. The results of the calculations are presented in Table 3. The calculated test value (F) was compared with the critical value (F_0), which is a function of the assumed confidence level and the number of degrees of freedom. The assumed confidence level was 0.05. The printing in Table 3 is similar to that in Table 2, with significant test values bolded and underlined, and values approaching the significance level in bold only.

Air temperature and wind direction were found to be the meteorological elements of importance as regards THC concentrations in the air over the testing area. In summer, cloudiness played an important role, too. The analysis of variance also included situations of the combined impact of wind velocity and direction. Test values F exceeding the critical point F_0, i.e. indicating the significant influence of the given meteorological element on THC concentrations around the Gdańsk Refinery Plant, were observed for wind velocities within the range 2.1 to 4.0 $m \cdot s^{-1}$.

Meterological situations influencing THC concentrations around the Gdańsk Refinery were defined on the basis of results of statistical analysis. Delimitation criteria were verified separately for the summer and winter half-years, because of the considerably different threshold values of the given meterological elements observed in the two seasons. The criteria for the delimitation of these situations are the following:

1. situations favourable to high THC concentration:
   a) summer half-year:
      — average daily wind direction: SE & E,
      — average daily air temperature: > 15.0°C,
      — cloudiness: < 2.0;
   b) winter half-year:
      — average daily air temperature: 5.1–15.0°C,
      — average daily wind direction: E & SE;
2. situations favourable to low THC concentration:
   a) summer half-year:
      — average daily wind direction: W & SW & NW,
      — average daily air temperature: 0.1–5.0°C,
      — cloudiness: > 6.0;
   b) winter half-year:
      — average daily air temperature: < –5.0°C,
      — average daily wind direction: NE.

In the cases of both situations favourable to high THC concentrations and situations promoting low THC concentrations, the analysis indicated the correct choice of criteria. In summer, as well as in winter, the individual effect and combined impact of meteorological elements on THC concentration and horizontal THC gradients, was marked by respectively higher or lower concentrations averaged for the entire testing area (Fig. 6, Tab. 4).

Aerosanitary conditions over the testing area were classified on the basis of average daily THC concentrations measured in the period 06.07.1980–31.07.1980. Three air quality classes were distinguished: advantageous conditions, moderate conditions and bad conditions. The frequency of bad conditions at particular measurement points was the deciding criterion of this classification; the bad conditions at a measurement point are characterized by the positive deviation of the average daily THC concentration from the average value for the entire testing area. The area, represented by the measurement points where positive deviation represented not more than 33.3% of the total number of results, were included in the class of advantageous conditions; the second class characterized enclosures with 33.4–66.7% of results with positive deviations and the class of bad conditions related to results with over 66.7% of positive deviations. The boundaries of enclosures were found by the interpolation method; with 33.3% and 66.7% isolines drawn to denote the frequency of occurrence of bad conditions.

TABLE 4. THC concentration ($\mu g \cdot m^{-3}m$) and horizontal gradient of THC concentration ($\mu g \cdot m^{-3}km$) around Gdańsk Refinery for various meteorological situations

Meteorological situation	THC concentration		Horizontal gradient of THC concentration	
	determined situation	whole period	determined situation	whole period
Situations favourable for THC concentration				
Summer half-year				
wind direction (E, SE)	470	390	452	287
air temperature (>15.0°C)	414		334	
cloudiness (< 2)	420		309	
combined impact	470		467	
Winter half-year				
air temperature (5.1–15.0°C)	700	555	962	549
wind direction (E, SE)	652		579	
combined impact	886		1439	
Situations favourable for low THC concentration				
Summer half-year				
wind direction (W, NW, SW)	351	390	207	287
air temperature (0.1–5.0°C)	354		246	
cloudiness (> 2)	359		243	
combined impact	243		147	
Winter half-year				
air temperature (< –5.0°C)	447	555	144	549
wind direction (NE)	418		313	
combined impact	534		188	

Source: Wyszkowski, 1994.

The central and south-eastern part of the Refinery grounds formed the enclosure with the highest air pollution hazard. It is in this area that the greatest number of anthropogenic hydrocarbon emission sources are situated, including typically technological installations, like petroleum-storage tanks, fuel distributors, etc., and sewage treatment plants, both of the Refinery and municipal. Beside those, the south–easterly surroundings of the Refinery

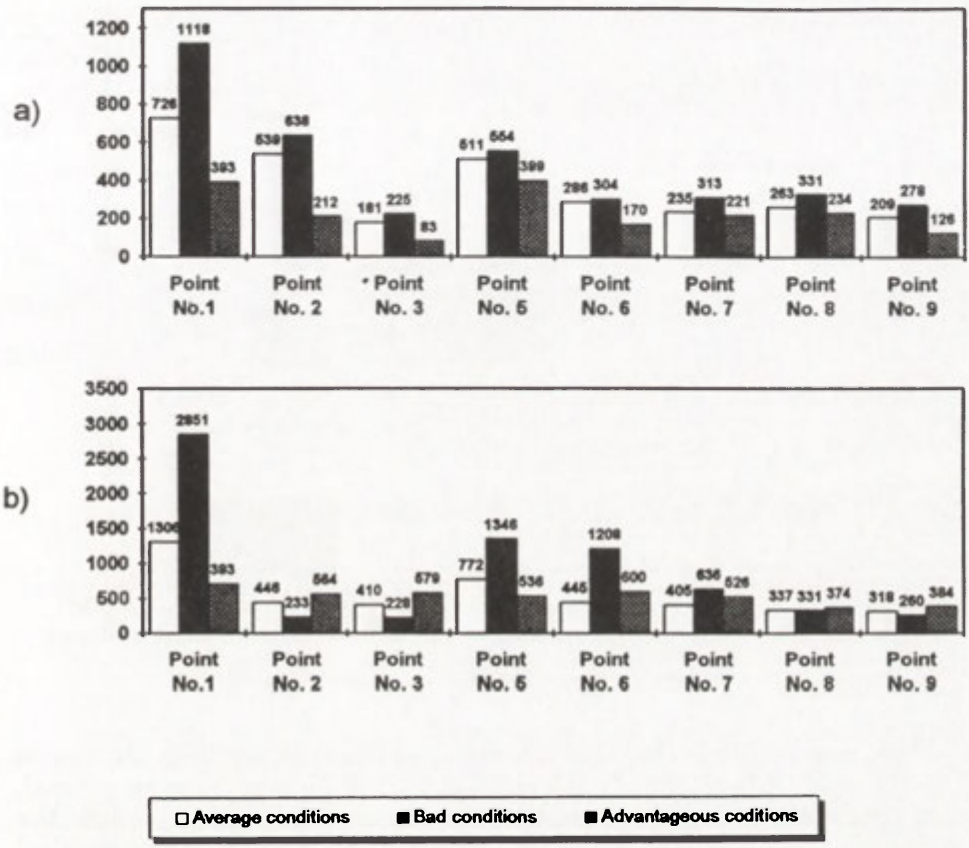

Fig.6. THC concentration around Gdańsk Refinery Plant in various meteorological situations: a — summer half-year, b — winter half-year

are formed by the vast, waterlogged Żuławy Wiślane area, which is a considerable natural source of emission of methane, mainly during a hot summer (Fig. 7).

The moderate hazard zone extended to the remaining part of the Refinery area and even farther to the north–east, i.e. in the direction of the mouth of the Wisła Śmiała river into the Gulf of Gdańsk. The relatively high THC concentration in this area is determined mainly by emission from tanks owned by the Enterprise of Oil Pipeline Exploitation that are installed on the northern bank of the Martwa Wisła river on one hand, and by the atmospheric transport of pollutants from over the Refinery on the other. A certain contribution is also brought in by local methane emission from damp soil.

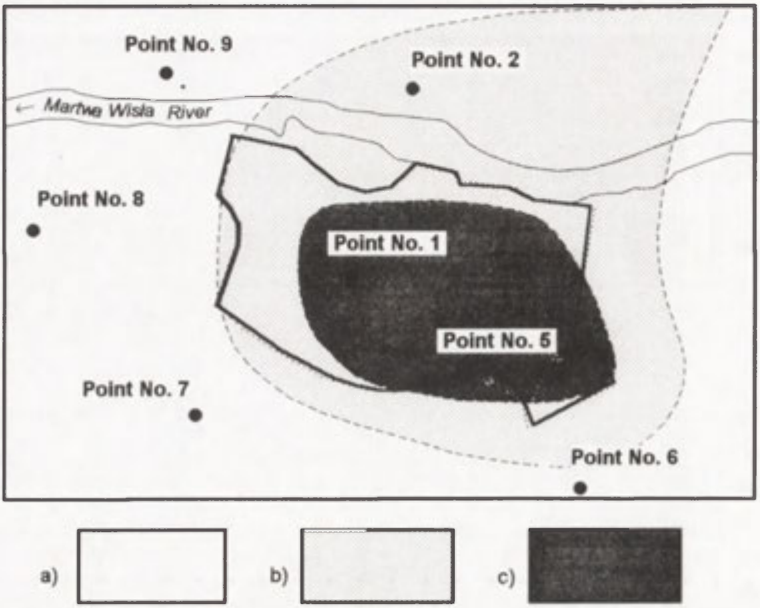

Fig.7. Air quality classes around Gdańsk Refinery Plant from the point of view of THC concentration: a — advantageous conditions, b — moderate conditions, c — bad conditions

CONCLUSIONS

The greater number of anthropogenic hydrocarbon emission sources in the Gdańsk Refinery are of moderate height, hardly over 20 m in general, and emission occurs in a disorderly manner as hydrocarbons pollute the atmosphere via evaporation from liquid products. Because of the physical properties of hydrocarbons — usually heavier than air, and the kind of THC emission sources, the dispersion of pollutants is rather limited. Thus, the hydrocarbon concentration in the air depends above all on emission magnitude. The results of the presented study point to air temperature and wind velocity as the meteorological elements of particular importance where the emission of hydrocarbons from anthropogenic sources is concerned. High air temperature and a wind velocity of 2–4 $m \cdot s^{-1}$ enhance the THC emission.

It seems very probable that the structure of the boundary layer over the Gdańsk Refinery plays an important role in the dispersion of hydrocarbons in the air. This observation is supported by the fact that, despite the significant positive correlation of THC concentrations with air temperature both in summer and winter, the average THC concentration in winter was still higher than that in summer. It appears that the reason for this can be found in the convectional structures dominating in summer and the inversive structures dominating in winter. However, the available experimental data did not suffice to verify this hypothesis so the study is going to be continued.

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HYDROCHEMICAL EFFECTS OF SUBMARINE GROUNDWATER DISCHARGE TO THE PUCK BAY (SOUTHERN BALTIC SEA, POLAND)

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ABSTRACT: The article presents alterations observed in interstitial water chlorinity and (^{18}O, D) isotope composition and in near-bottom salinity caused by groundwater discharge to the Puck Bay from Cretaceous, Tertiary and Quaternary aquifers. The groundwater seepage decreases the chlorinity of interstitial water and the salinity of near-bottom water. The comparison of the oxygen and hydrogen isotope composition of underground, interstitial and near-bottom waters indicated a reduction of the content of heavy isotopes in the interstitial water and thus gave evidence of freshwater seepage through the sea floor. Zones with abnormal interstitial water chlorinity and diminished salinity of near-bottom water were used to determine drainage areas for fresh groundwater on the Puck Bay bottom.

KEY WORDS: submarine groundwater discharge, chlorinity of porewaters, salinity of near-bottom waters, isotope (^{18}O, D), Puck Bay, Baltic Sea.

INTRODUCTION

Groundwater discharge from the land into the sea induces various chemical-physical alterations in the marine environment. The character of ensuing alterations depends mainly on discharge magnitude, the way in which underground water is entering the marine environment and discrepancies in chemical composition between groundwater and sea water.

The hydrochemical effects of groundwater discharge into the sea are particularly well-marked in the pore water of marine sediments and in the near-bottom water. The analyses of chemical anomalies caused by this discharge lead to the determination of drainage areas of underground water on the sea floor as well as to the evaluation of the intensity of groundwater discharge.

The article presents the results of a study carried out in the Puck Bay concerning the alterations of pore water chlorinity, near-bottom water salinity and pore water isotope (^{18}O, D) composition caused by groundwater seepage.

The area of the Puck Bay forms a semienclosed basin in the western part of the Gulf of Gdańsk, characterized by relatively low salinity; the average being 7,6 PSU (Nowacki 1993). Maximal concentrations of Cl^- ions only infrequently exceed 5 g dm^{-3}, with the average being 3.5–4.0 g dm^{-3}. Such concentrations are 100 times greater than those recorded in the groundwater of the coastal zone of the Puck Bay, which usually fall in the range 5–20 mg dm^{-3}, and occasionally reach 50 mg dm^{-3}.

As regards hydrogeological conditions, the Puck Bay is the major drainage area of the Cretaceous, Tertiary and Quaternary coastal aquifers (Dowgiałło and Kozerski 1975; Sadurski 1986). The Bay affects the directions of the underground flow and models the regime of the groundwater piezometric surface. Seismoacoustic profiling conducted in the Bay (Jankowska et al. 1992) showed a series of permeable deposits under the sea floor, extending from the coast of the water horizons.

Groundwater discharge into the Puck Bay occurs mainly by ascensic seepage through the seabed, with the one exception of the Hel Peninsula, where groundwaters from Holocene aquifers flow in an unrestricted stream along the shore line directly into the sea (Piekarek-Jankowska 1994).

Groundwaters contained in the Cretaceous, Tertiary and Quaternary strata are fresh. Cretaceous water belongs to the HCO_3–Na type with a total mineralisation of 300–600 mg dm^{-3}. Tertiary and Quaternary waters are of the HCO_3-Ca type, with a total mineralisation of 150–450 mg dm^{-3}. The temperature of the groundwater approaches the value of the multi-year mean air temperature, i.e. 6–7°C.

MATERIAL AND METHODS

Bottom sediment samples for analyses of interstitial water were collected at 28 stations using gravity corers of the KAJAK and GOIN types. The locations of sampling stations are presented in Fig. 1. The cores were segmented into 5 cm slices directly after sampling and kept frozen until analyses were performed in the laboratory. Porewater was withdrawn mechanically according to the method described by J.A. Robbins and J. Gustinis (1967). The concentration of Cl^- ions was determined after the Mohr-Knudsen method (Grasshof 1976).

Measurements of the hydrological structure of seawater were conducted at 38 stations and transsections with a total length of 20 km (Fig. 1). The transsections were oriented following hydrogeological criteria; i.e. following the directions of groundwater flow and perpendicularly to the assumed drainage zones.

Water conductivity (± 0.1 mS cm^{-1}) and temperature (± 0.05°C) were recorded for every 0.5 dB of pressure with an automatic CDT probe (Meerestechnik-Electronik GmbH). These data were used to determine salinity in accordance with UNESCO algorithms (1980).

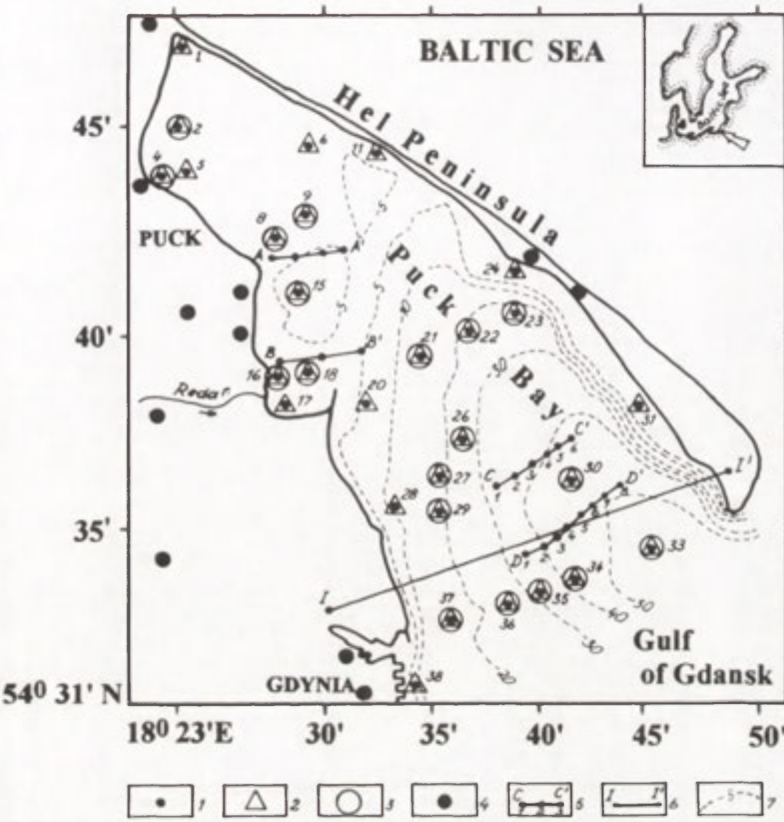

Fig. 1. Study area

Measuring stations: 1 — salinity of seawater, 2 — chlorinity of porewater, 3 — $\delta^{18}O$ and δD in near-bottom water and porewater, 4 — $\delta^{18}O$ and δD in groundwater; 5 — salinity transect (Figs. 10,11), 6 — line of hydrogeological section (Fig. 2), 7 — isobath

The oxygen and hydrogen (^{18}O, D) stable isotope composition of near-bottom water (0.2–0.5 m above the bottom) and pore water (from 5 cm sediment segments) was determined in samples taken at 18 stations (Fig. 1). The oxygen stable-isotope analyses were performed in a VG Sira 10 mass spectrometer with an automatic inlet. The hydrogen stable-isotope analyses were carried out in a Finningan Mat 250 triple collector mass spectrometer. The results of both measurements are expressed in per mill (‰) deviation from the SMOW standard using the δ-scale (Epstein and Mayeda 1953).

Continuous seismoacoustic profiling was done with a EGG Uniboom 230 apparatus Model 230. The total length of acoustic profiles took ca.100 km. The results of this study enabled the main lithological series to be distinguished and the occurrence of groundwater horizons below the sea bottom to be investigated (Fig. 2).

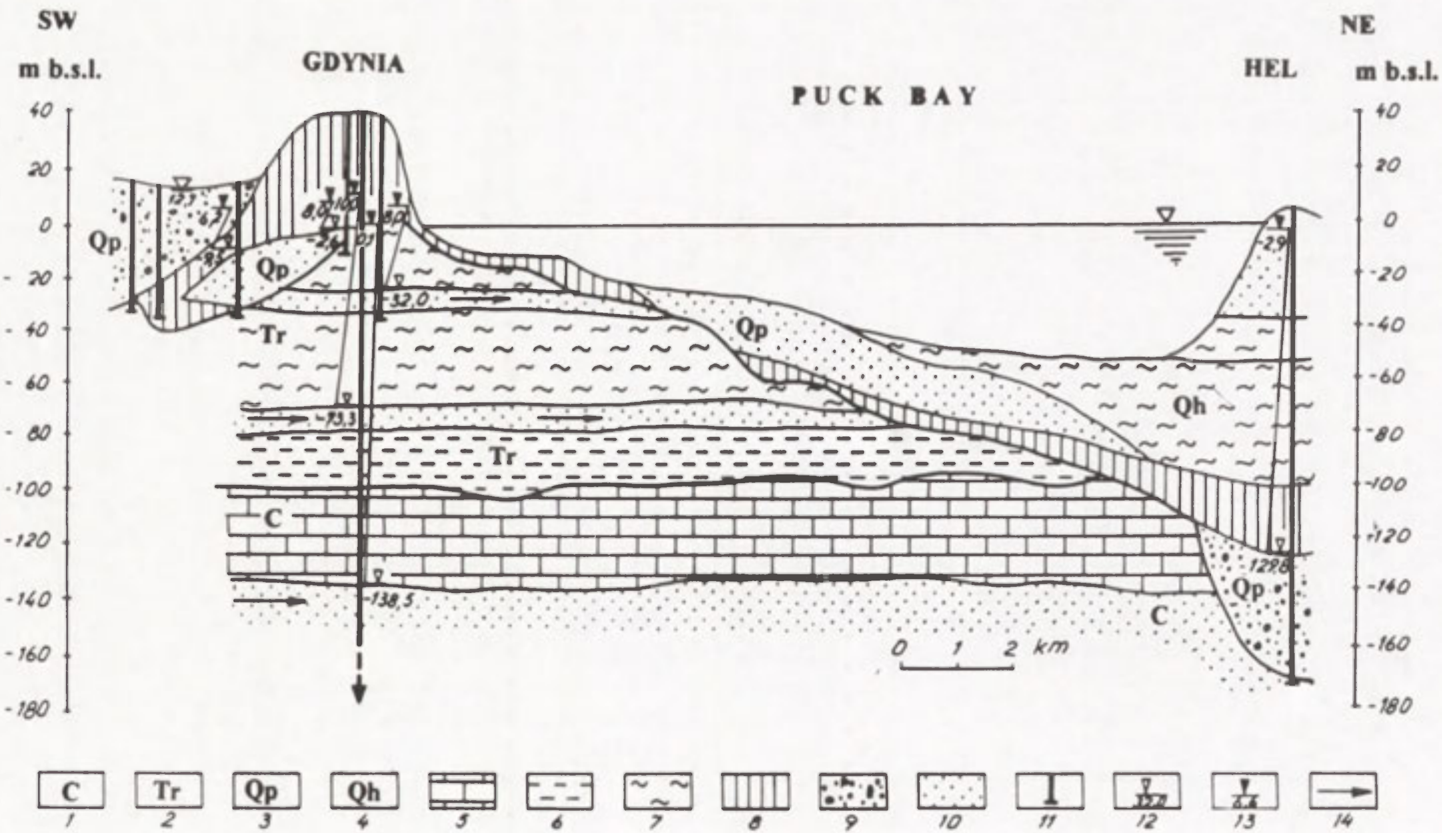

Fig. 2. Hydrogeological section I–I'

1 — Cretaceous, 2 — Tertiary, 3 — Quaternary-Pleistocene, 4 - Quaternary-Holocene, 5 — marl, 6 — clay, 7 — silt, 8 — boulder clay, 9 —sand-gravel, 10 — sand, 11 — well, 12 — top of aquifer, 13 — piezometric groundwater level, 14 — direction of groundwater flow

RESULTS AND DISCUSSION

CHLORIDE IONS IN THE POREWATERS

The main reason for choosing chloride ions as an indicator of groundwater flow through the marine sediments was the difference between their concentrations in fresh underground water from the coastal zone of the Bay and in saline seawater (Fig. 3) as well as the specific chemical properties of the chloride ion. The chloride ion neither forms insoluble compounds with macrocomponemts of seawater nor accumulates in marine organisms, and its distribution is independent of the chemical and biogenic composition of marine sediments (Brusylovsky and Lapteva 1976). Due to the considerable solubility of chloride salts it is scarce in marine sediments, though 97–99% of the total chloride content is found in interstitial water (Shyshkhina 1972). Chloride ions practically do not yield adsorption, and are on the contrary active hydrochemical migrants (Macioszczyk 1987).

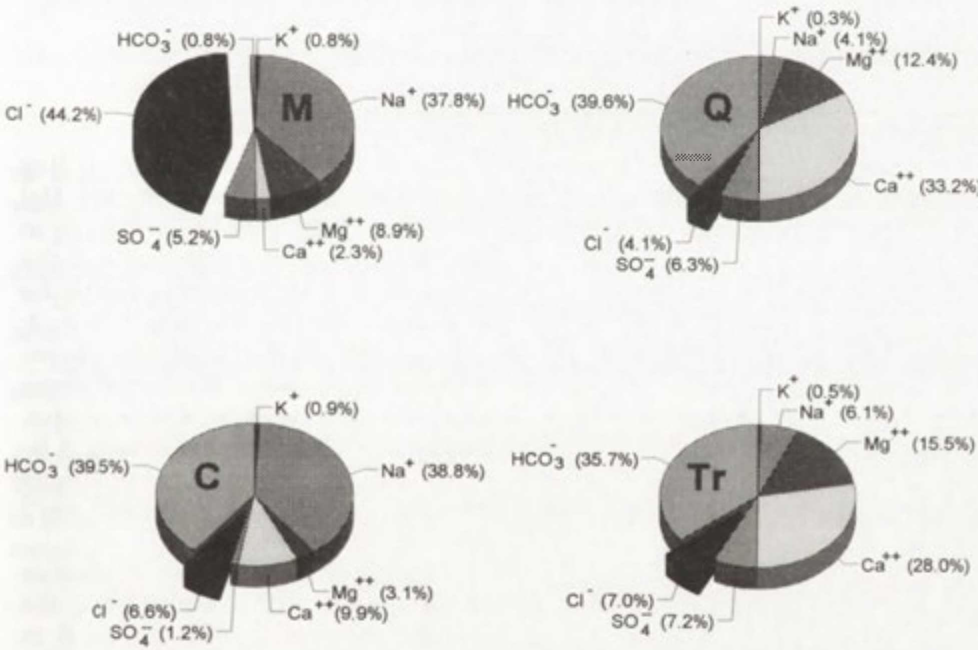

Fig. 3. Chemical composition of Puck Bay waters and groundwaters from coastal aquifers (average values)
M — marine water, Q — Quaternary aquifer, T — Tertiary aquifer, C — Cretaceous aquifer

Studies on the chlorinity of pore waters of Baltic sediments indicated that chloride concentration decreases slightly with the depth of the sediment profile, the mean decrease gradient being < 0.01 g dm^{-3} cm^{-1}, and chloride concentrations similar to those found in the near-bottom water occur down to 2 m below the seabed (Kullenberg 1952; Manheim 1976).

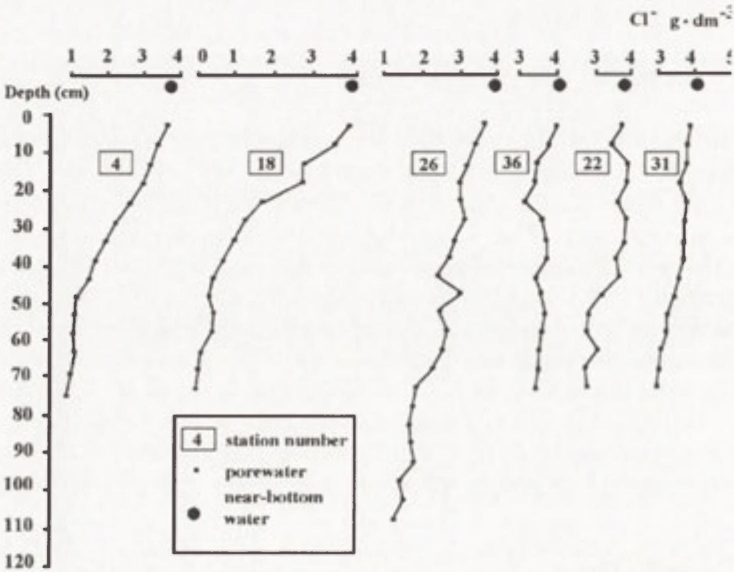

Fig. 4. Distribution of chlorinity of porewaters at chosen stations

Chlorinity analyses of interstitial water in sediments of the Puck Bay showed similar tendencies only in a restricted area adjacent to the Hel Peninsula scythe. The concentrations of Cl^- are relatively uniform here in the vertical sediment profile and the slight decline with depth is due to the gradient < 0.01 g dm^{-3} cm^{-1} (Fig. 4; stations: 36, 22, 31). Chloride concentrations in sediments farther off-shore showed much greater discrepancies. They fall within the wide range 4.0–0.37 g dm^{-3}, with vertical gradients from 0.01 to over 0.05 g dm^{-3} cm^{-1} (Fig. 4; stations: 4, 18, 26).

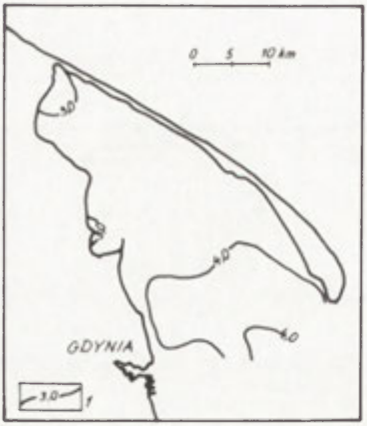

Fig. 5. Chloride ion distribution in porewaters within the bottom deposits layer at 0–5 cm
1 — isoline of chloride ion concentration (g dm^{-3})

A particularly well-marked influence of fresh water was observed along the western shore of the Bay, to the 5 m isobath. The concentrations of Cl^- in the pore water of the surface (0–5 cm) sediment layer reached 3.0–3.5 g dm^{-3}, at 20–25 cm depth below the sea floor they diminished to 2.0 g dm^{-3}, and at 40–45 cm depth to 1.0 g dm^{-3} (Fig. 5, 6 and 7).

Regarding the distribution of chloride ion concentrations in porewater, marked

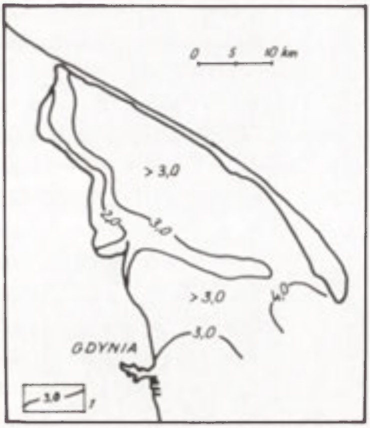

Fig. 6. Chloride ion distribution in porewaters within the bottom deposits layer at 20–25 cm
1 — isoline of chloride ion concentration ($g\ dm^{-3}$)

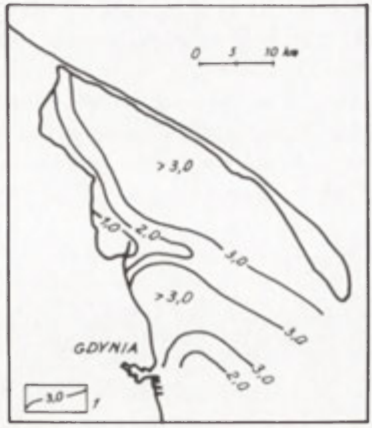

Fig. 7. Chloride ion distribution in porewaters within the bottom deposits layer at 40–45 cm
1 — isoline of chloride ion concentration ($g\ dm^{-3}$)

as the vertical gradient ΔCl [$g\ dm^{-3}\ cm^{-1}$], the sea floor of the Puck Bay was divided into three areas (Fig. 8):

I — an area with practically constant chloride concentration and a vertical gradient $\Delta Cl < 0.01\ g\ dm^{-3}\ cm^{-1}$,

II — an area with gradual decline of chloride concentrations with depth and the gradient $0.01\ \ \Delta Cl\ \ 0.05\ g\ dm^{-3}\ cm^{-1}$,

III — an area with rapid decrease of chloride concentrations with depth, and the gradient exceeding $0.05\ g\ dm^{-3}\ cm^{-1}$.

The relatively rapid decline of chloride concentrations in interstitial water areas II and III is probably caused by the discharge of fresh groundwaters. This assumption was supported by sodium-chloride indicator determination in porewaters of this region (Tab.1). The indicator values remained relatively constant in the vertical profile of sediments in area I, with the mean of

TABLE 1. Sodium-chloride indicator values found in porewaters and near-bottom waters of the Bay of Puck

$r\frac{Na^+}{Cl^-}$	Porewaters			Near-bottom water
	Area I	Area II	Area III	
Min.	0.78	0.85	0.87	0.83
Max	0.88	0.97	1.01	0.86
Mean	0.85	0.91	0.94	0.85
n*	69	45	88	30

n* — number of data

0.85 being equal to the value found for the Puck Bay seawater. Thus, porewaters of this region turned out to be the contemporary sedimentary waters, not coming into contact with water of different genetic origin. The sodium-chloride indicator in areas II and III ranged from 0.85–1.01 and gave evidence of the porewater contact with freshwater infiltrating the sediments. According to Z. Pazdro and B. Kozerski (1990) indicator values close to 1 and exceeding this level point to an intensive exchange between fresh and saline water.

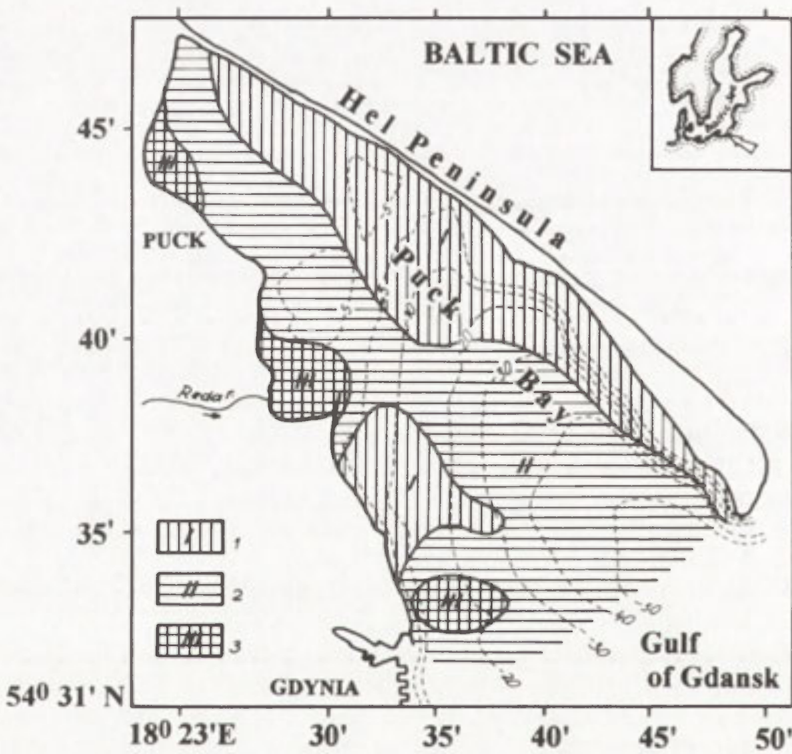

Fig. 8. Gradients of chloride ion concentration in porewaters (g Cl^- dm^{-3} cm^{-1})
1 — ΔCl < 0.01, 2 — 0.01 < ΔCl < 0.05, 3 — ΔCl > 0.05

SALINITY OF NEAR-BOTTOM WATER

There are two major forces influencing the salinity in the Puck Bay: seawater from the Gulf of Gdansk and the riverine inflow. A typical salinity distribution shows an increase with depth in the water column. The western part of the Bay reveals lower salinity (7.31 PSU) due to shallowness, riverine water inflow and the obstructed exchange with the Gulf through transverse banks. The increase of salinity with depth is marked by a vertical gradient < 0.01 PSU m^{-1}. The salinity in the western part of the Bay is slightly higher; 7.65 PSU. The salinity gradient reaches 0.01 PSU m^{-1} to a depth of 30 m and below increases to 0.02 PSU m^{-1}. The discrepancies between salinity gradients are the resultant of the density-thermic stratification ensuing from the intensive exchange of water with the Gulf of Gdańsk (Nowacki 1993).

Studies regarding the hydrological structure of water in the Puck Bay showed certain abnormalities; in some areas salinity decreased in the near-bottom water. In the coastal strip of the north-western part of the Bay these anomalies include nearly the entire water column, because the salinity decrease is already noticeable at 0.3–0.5 m depth and falling down to the bottom (Fig. 9). The differences in salinity between surface and near-bottom water reach from 0.5 to 0.3 PSU. In areas with abnormal salinity distribution the water temperature takes an exceptionally constant values along the vertical profile. The absolute values of the temperature gradient are 0.01–0.05°C m^{-1}.

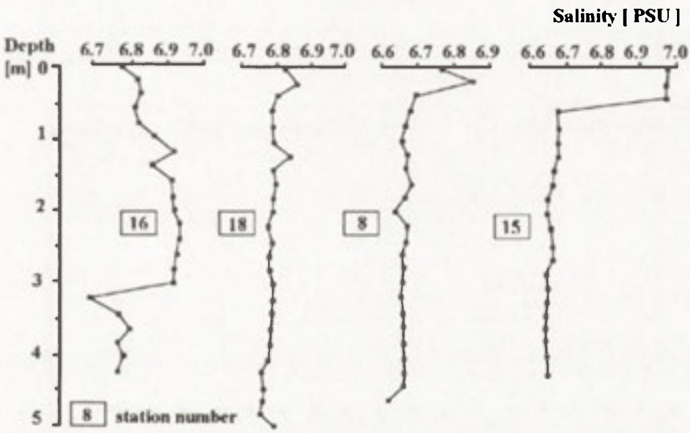

Fig. 9. Examples of the salinity vertical distribution in the shallow water part of Puck Bay

Salinity inversions were also observed in the deeper part of the Puck Bay in the near-bottom water layer of 4–20 m width. The inversions can be classified into two types; one involves a near-bottom water layer covered by a layer of more saline water (Fig. 10), with the stability of the two layers maintained due to a significant negative temperature gradient (–0.33°C m^{-1} to –0.7°C m^{-1}). The other type of inversion reveals a pulsatory character resulting from the upward movement of colder, less saline water intrusions (Fig. 11). Salinity anomalies are encountered below the thermocline. In order to define the character of this movement, the effective Rayleigh number was calculated (Turner 1973). The calculated values exceeded the second critical number, equal to 50 000, and this, according to Druet (1994), is a symptom of turbulent convection.

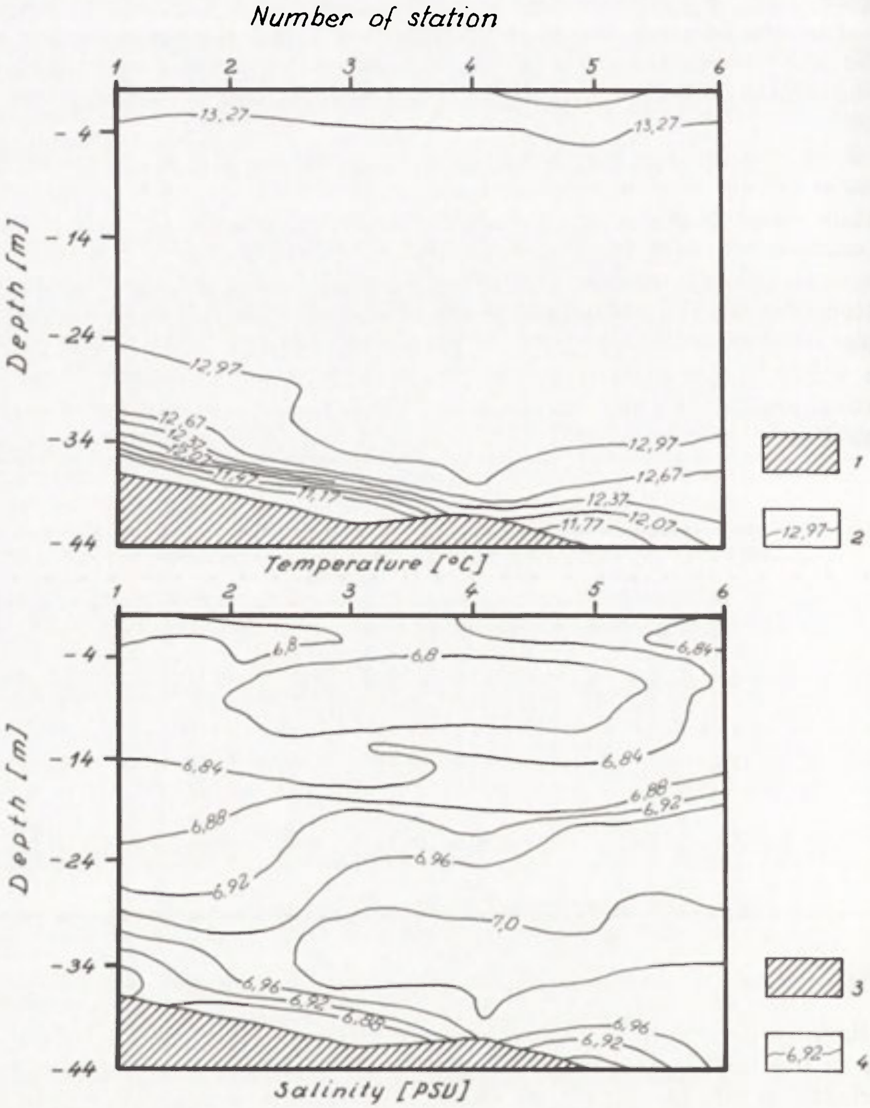

Fig. 10. Salinity and temperature of water distribution on the CC' transect (June, 1993)
1, 3 — sea bottom, 2 — isotherm, 4 — isohaline

The presented salinity anomalies can be attributed solely to fresh groundwater discharges, because the general principles of the Puck Bay water circulation and exchange exclude the possibility of other types of salinity inversion (Nowacki 1993; Jankowski 1984). Thus, the pressing conclusion was that near-bottom areas with diminished salinity indicate the approximate drainage zones of fresh groundwater.

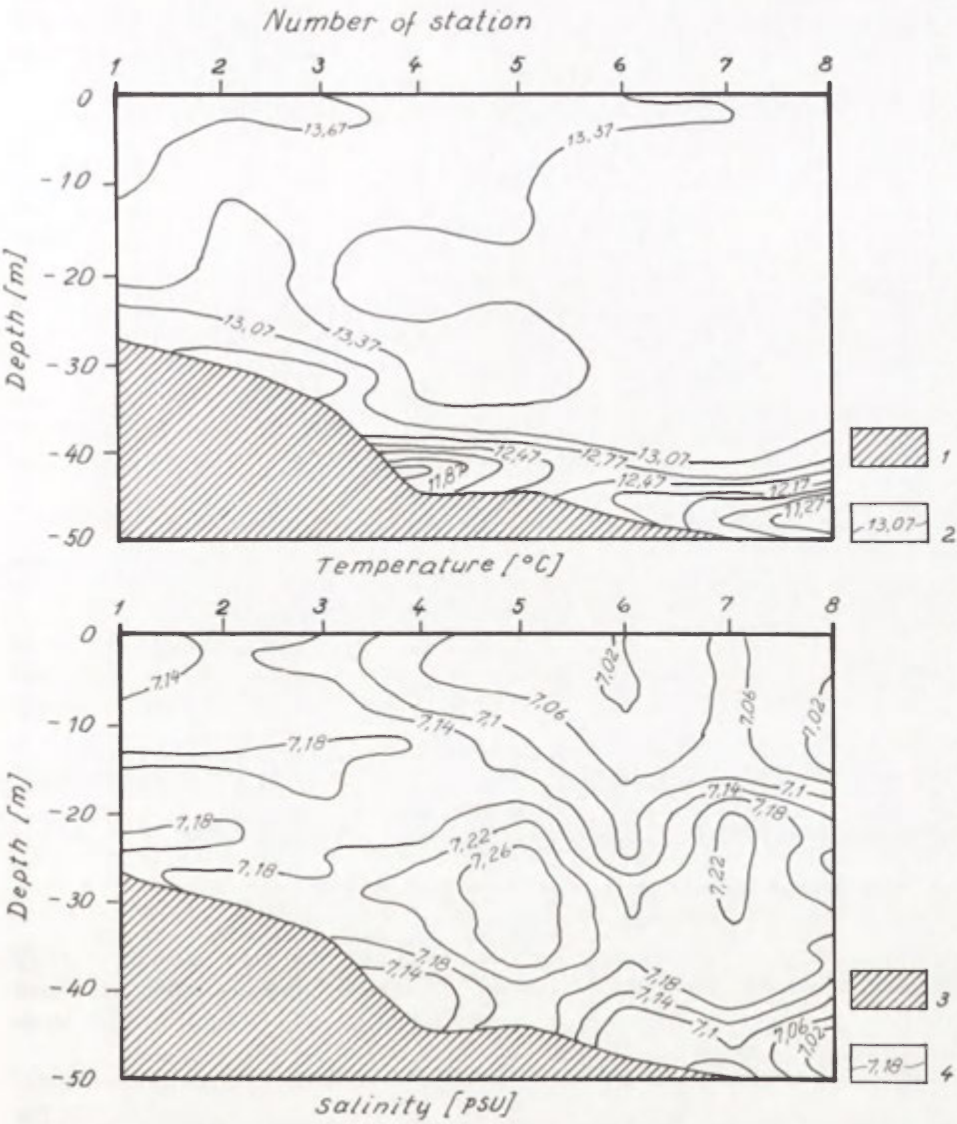

Fig. 11. Salinity and temperature of water distribution on the DD' transect (June, 1993). Legend as in Fig. 10

Taking into account the differences of salinity at 5 m above the sea floor and at the water-sediment interface, the Puck Bay bottom was classified into several regions. The diminished salinity zones were also determined (regions III and IV), where these differences turned negative, from –0.02 to –0.2 PSU (Fig. 12).

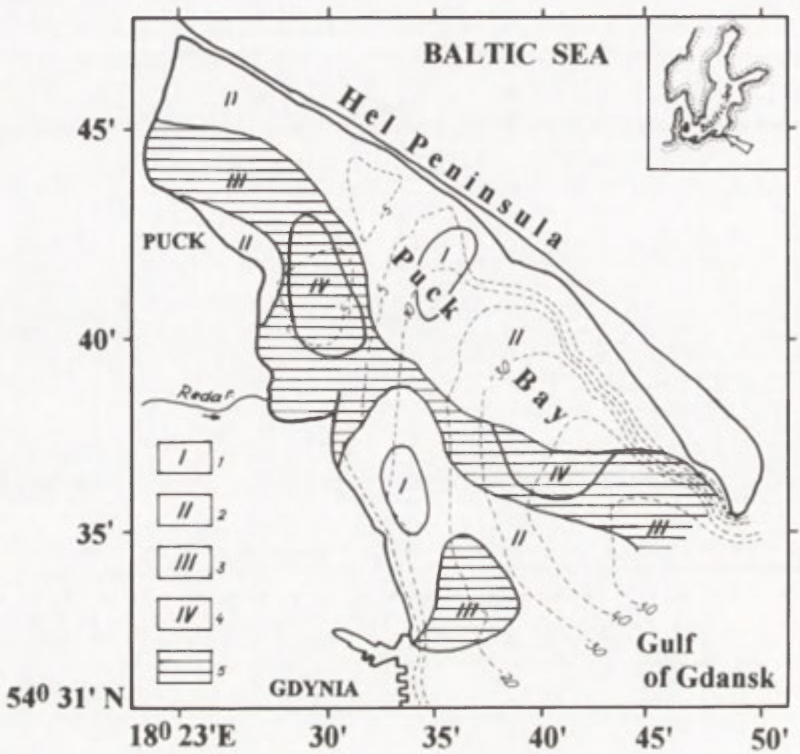

Fig. 12. Gradients of the salinity in near-bottom waters (5 m layer above sea bottom)
1 — $+0.1 < \Delta S < +0.2$, 2 — $+0.01 < \Delta S < +0.1$, 3 — $-0.02 < \Delta S < -0.01$, 4 — $-0.2 < \Delta S < -0.1$,
5 — salinity decreasing zone

OXYGEN AND HYDROGEN STABLE-ISOTOPE STUDIES

The composition of oxygen and hydrogen isotopes was used to identify the origin of fresh water in the marine sediments. These isotopes were also analysed in the near-bottom sea water and in groundwater from the Quaternary and Tertiary coastal aquifers (Fig. 1).

The mean oxygen and hydrogen isotope composition of the modern infiltration waters of meteoric origin in the Gdansk region is about –10‰ for $\delta^{18}O$ and about –70‰ for δD (Zuber et. al. 1990). Typical ranges of isotope content in waters from different aquifers are given in Table 2. The large scatter of data for water from the Cretaceous aquifer can be explained by the presence of glacial-age infiltration in the northern parts of the aquifer. In some areas this glacial water is ascending to the overlying younger formations (Zuber et al. 1990)

The $\delta^{18}O$ and δD of oceanic seawater are close to zero and vary only within narrow limits (Faure 1986). In the Baltic Sea, the isotope composition varies from the values close to those of meteoric waters in the Botnicka Bay region to the values near the North Sea (Fröhlich et al. 1988). Intermediate values are observed in the Gulf of Gdansk (Tab. 3).

TABLE 2. Oxygen and hydrogen isotopic compositions of the groundwater samples from the coastal zone of the Puck Bay

Aquifer	n*	$\delta^{18}O$ (‰vs. SMOW)		δD (‰vs. SMOW)	
Quaternary	14	–10.1	–10.7	–67	–72
Tertiary	7	–9.9	–10.7	–67	–71
Cretaceous	5	–9.9	–14.4	–68	–102

n* — numer of data

TABLE 3. Oxygen and hydrogen isotopic compositions of the sea water samples from the Gulf of Gdansk (by Frohlich et al. 1988)

Latitude (deg)	Longitude (deg)	Depth (m)	$\delta^{18}O$ (‰ vs. SMOW)	δD (‰ vs. SMOW)
54°42.0' N	19°11.8' E	2.1	–6.7	–54
		21.5	–7.0	–53
		95.9	–6.4	–47

The isotope composition of the sediment porewaters from the Puck Bay is shown in Fig. 13, together with data for the near-bottom water. It is clear from that figure that the near-bottom water has an isotope content close to typical values for the Bay (cf. Table 3), though, on average, slightly shifted

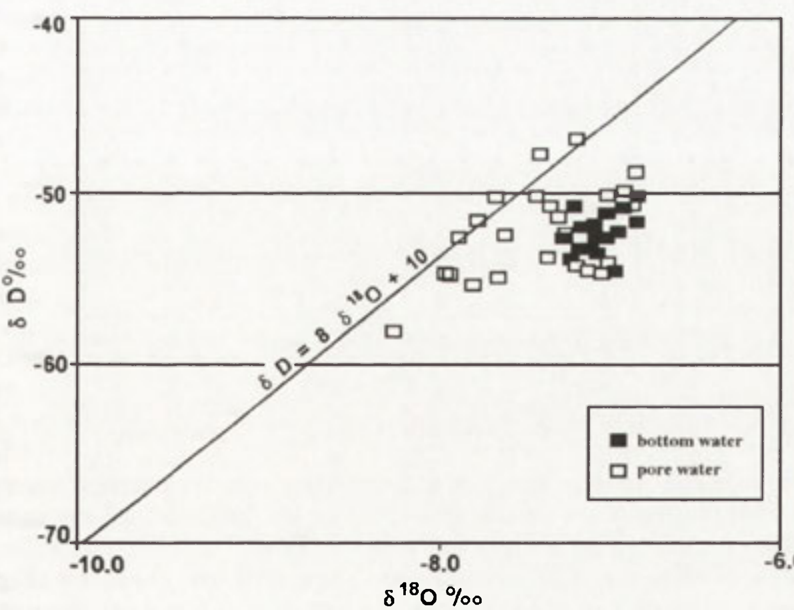

Fig. 13. Oxygen and hydrogen isotopic compositions of near-bottom waters and porewaters

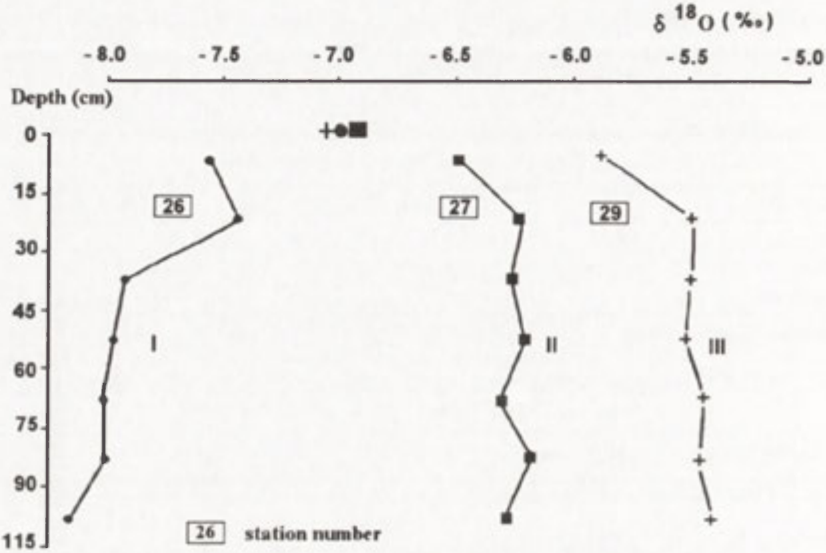

Fig. 14. Types of distribution of $\delta^{18}O$ in porewaters

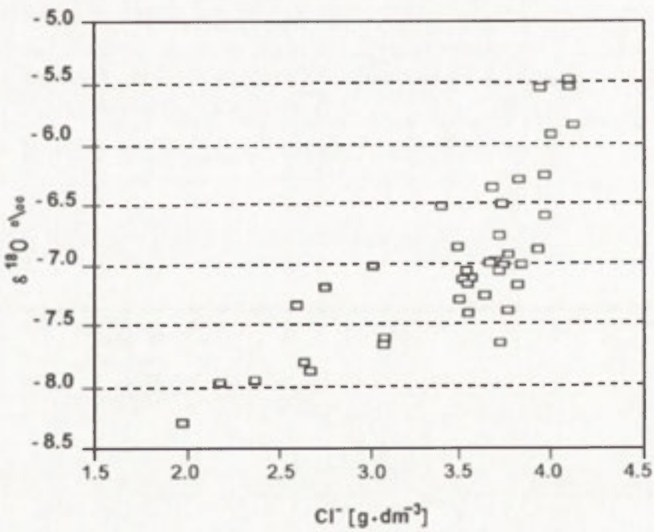

Fig. 15. Relationships between $\delta^{18}O$ and Cl^- in porewaters

to more negative values. The porewater values are on average even more shifted to more negative values, attesting to the influence of seepage from the aquifers discharging their waters to the Bay.

Isotope profiles taken at several sites show different character (Fig. 14). The first type (I in Fig. 14) indicates the actual seepage from the aquifers. The second and third types show no trend within the investigated depth, and the constant isotopic values may result either from the lack of seepage or from the reversed process due to strong exploitation of the Cretaceous aquifer and possible large extension of the drawdown zone under the bay bottom.

The mixing between aquifer and bay waters marked in the composition of the porewater (see profile I in Fig. 14) is generally confirmed by the correlation between the $\delta^{18}O$ and Cl^- contents (Fig. 15).

CONCLUSIONS

Hydrochemical changes in the aqueous environment of the near-bottom and interstitial water of the Puck Bay, as well as the content of isotopes $\delta^{18}O$ and δD in these waters, indicated submarine drainage of fresh groundwater through the Bay's floor. Similar hydrochemical effects of submarine discharge have been observed in various marine basins (Johannes and Hearn 1985).

Groundwater discharge into Puck Bay is most clearly marked in the porewaters as the decrease of chlorinity along the vertical sediment profile. The decrease of salinity is shown in significant gradients, frequently exceeding 0.05 g dm^{-3} cm^{-1}. Groundwater discharge also causes salinity inversion of near-bottom water. In areas of intensive freshwater seepage, the salinity of the water layer 5 m above the bottom is 0.2 PSU lower than in the overlaying water. The effects of groundwater discharge are also clearly marked in the isotopic composition of porewaters. Due to the mixing of synsedimentary waters with groundwater, less abundant in heavy isotopes, the values of $\delta^{18}O$ and δD are shifted towards the negative pole as compared with the typical composition of marine near-bottom water. The extension of described hydrochemical changes determines the approximate boundaries of drainage zones of fresh groundwater in the bottom of the Puck Bay (Fig. 16). Though it has to be borne in mind that the seabed areas with diminished chlorinity of porewater do not coincide exactly with the location of areas with diminished salinity of the near-bottom water. This is evidently because the groundwater discharge into the Puck Bay is relatively small and its main type is seepage. The average discharge was evaluated to take 4.7 dm^3 s^{-1} per 1 km^2 of sea floor (Piekarek-Jankowska 1994). The hydrochemical effects of so slow a process are much better distiguishable in the more stable medium of interstitial waters than in the dynamic near-bottom water. For example; along the salinity profile DD' (Fig. 11) the fresh water layer is present only in the eastern part of the basin, while the profile runs along an area of decidedly decreased chlorinity of porewaters.

In accordance with the described anomalies in chemical composition of near-bottom water and porewater are the results of diatom flora studies by A. Witkowski (1993) in the Puck Bay. The author found local populations of fresh water diatoms, untypical of the brackish Puck Bay water (*Achnanthes*

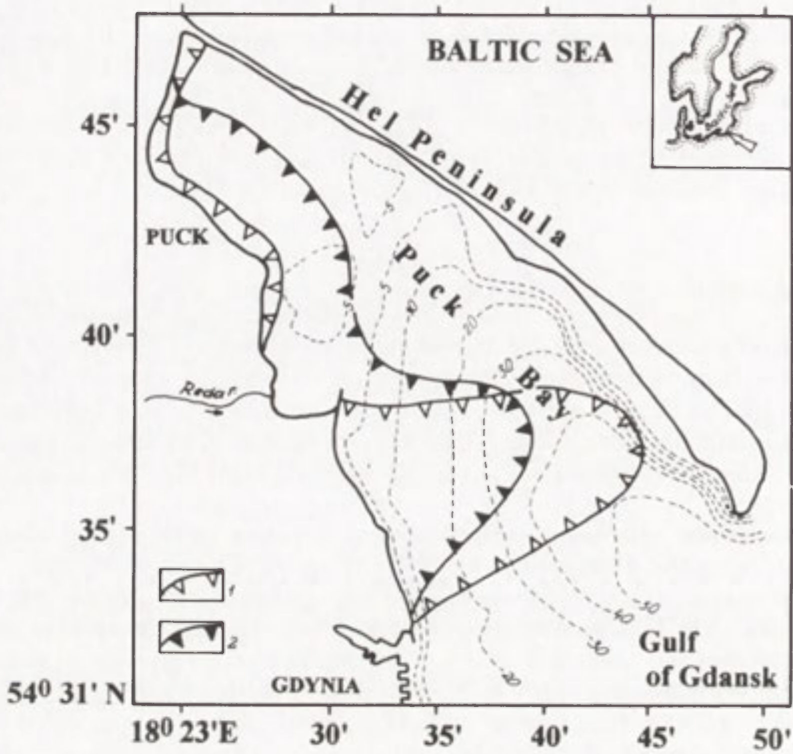

Fig. 16. Drainage zones of fresh groundwater on bottom of Puck Bay
1 — Quaternary groundwaters, 2 — Tertiary groundwaters

clevei, *A. nitidiformis*, *A. inariensis*, *Diploneis oculata* i *Navicula mollicula*). These species are characteristic of fresh waters abundant in carbohydrates. The locations of these diatom aggregations in the Puck Bay were within the drainage zones of carbohydrate groundwaters. Seemingly, these diatoms could be used in the Puck Bay as bioindicators of groundwater discharge.

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TOWARDS A MORE OPERATIONAL FORM OF THE IDEA OF SUSTAINABLE DEVELOPMENT

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ABSTRACT: The author starts from the assumption that the idea of sustainable development will remain merely an attractive slogan of limited application if it is not given an operational form. It is therefore necessary to search for ways of making it operational. The author suggests two ways he considers promising: one inspired by the theory of economic development and the other by the theory of synergetics. To approach the targets of sustainable development, the present structure of ecological-economic systems requires a pro-ecological transformation. It follows from the theory of economic development that a necessary condition for such a transformation is the discontinuity of the functions of demand, production, saving, and straining and regeneration of the natural environment. Synergetics, in turn, suggests tracing the transition from micro-scale changes to macro-scale ones, and then the transition of complex systems from one level of complexity to another.

KEY WORDS: operational definition of sustainable development, pro-ecological transformation of economic system, theory of economic development, theory of synergetics, ecological-economic information.

INTRODUCTION

Sustainable development is not a natural, spontaneous process occurring without the interference of an intelligent society. Its conception is a property that the intelligent society assigns to its strategy of economic development and environmental protection. The aim of this strategy, as defined in the report of a UN commission headed by Ms Gro Harlem Brundtland, is an economic development involving man's interference with the natural environment that will satisfy the needs of the present generation without jeopardising the ability of the future ones to meet their own needs.

In recent years, many works have been performed that have made reference to the idea of environmentally-sustainable development. To this day, however, this has no operational form from which principles of socio-economic, spatial and regional policies could be derived. Studies striving towards this aim can draw inspiration from the concepts of various scientific disciplines investigating the dynamics and transformations of complex systems. The present article[1] relies on the theory of economic development and the theory of synergetics. It is hoped that in this way it will be possible to avoid the weakness of concepts based on ethical arguments and references to the human species' will to survive. Ecologically sustainable development is expensive. The decision to bear the cost rests with societies and their governments, including local and regional governments. Governments make decisions in accordance with opinions expressed by societies (voters), but they also try to influence these opinions with the help of rational arguments. Especially persuasive are economic arguments for the feasibility of particular ecological-economic strategies (Domański 1992).

AN APPROACH INSPIRED BY THE THEORY OF ECONOMIC DEVELOPMENT

The question arises as to whether it is possible to have a strategy of sustainable development that would not only overstretch state and local budgets, but also generate new impulses for development and so, after an initial stage of substantial investments, place the economy on a new trajectory at least as dynamic and effective as the previous one. We cannot bear this hypothesis out as yet, but we can put forward arguments supporting it.

The transition to ecologically sustainable development, as to a significantly changed structure of any system, requires some conditions to be fulfilled. First of all, the shapes of functions characterising the economy and its relations with the natural environment have to change. They should be strongly nonlinear in the period of forced radical changes in the economy and the environment. This condition is met when the functions are discontinuous, or when their derivatives change stepwise (Solow 1970). In what follows we shall use the term 'discontinuity'. The discontinuity condition should be satisfied by the functions of demand, supply, saving and capital, as well as the strain on and regeneration of the natural environment.

It is a justified assumption that the policy of sustainable development will tend to create new demand, new markets for economic commodities. It is not a sufficient condition, however. The rise in demand should be a steep one, too (owing to investment concentration and multiplier effects). At the regional scale, it can be boosted further by improving the environment and thus making it more attractive to economic activities stimulating demand. Concurrent measures should depress the demand for ecological commodities thanks to a reduction in resource consumption and environmental pollution under the influence of a change in the structure of socio-economic needs

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(dematerialisation of production and income). Hence, the functions of demand for economic and ecological commodities should fluctuate (rise or fall) in a non-linear, and sometimes stepwise, fashion.

The production function can increase at an accelerated rate owing to the choice of efficient structure and sequence of investments and the use of productive capacity and infrastructure reserves. It is also possible to influence the productivity of ecosystems and their carrying and regenerative capacities.

The discontinuity of the saving function is a condition of securing the means for investments transforming the economy and its relations with the environment. One of the arguments of this function is the capital-income ratio. The higher it is, the worse, because this means that gaining an income requires a greater effort on the part of society (saving more).

The necessity of concentrating the infrastructural and production investments essential to putting the ecological-economic system on the trajectory of sustainable development as a rule means the need for foreign capital supply. However, this capital may produce inflationary impulses owing to the stimulation of multiplier demand. These can be weakened through additional import to offset this demand. The concept of saving and generating capital that is used in the economy can also be applied to ecological systems. Recently, to use the terms adopted here, the idea has been put forward of measuring natural capital with indicators of biodiversity (as defined at the levels of genes, species and ecological systems).

The overlapping consequences of function discontinuity define the conditions of development and the possibilities for the structural transformation of the ecological-economic system aiming at its sustainable development. When the concept of sustainable development is considered at the regional and urban scales, the list of conditions for its implementation grows longer. At the regional scale, the two general conditions (the prosperity of the present generation and the chance to satisfy the needs of future ones) have to be supplemented by a third, namely that the economic development of the given region should not jeopardise the sustainable development of neighbouring as well as distant regions. Moreover, the prosperity condition acquires a new dimension at this scale. The only kind of strategy that has a chance to be implemented is one that at least does not bring down the level of wealth and indicates opportunities for its growth. Its lowering might incline valuable individuals to migrate and weaken the impulses to develop enterprise, and in effect it might cause the level of innovativeness and regional income to go down.

As to the conditions of sustainable development at the urban scale, including the scale of large cities, specialists seem to have reached a general consensus of opinion. They suggest energy and resource saving as well as the renewal, modernisation and development of towns while preserving their technical, economic, social and cultural qualities. These requirements can be fulfilled by: a moderate density of the building-up of large cities and their links with smaller towns developing in the neighbourhood (the so-called decentralised concentration), the renewal and modernisation of city centres, taking care of green areas and, where possible, designing them in such a way as to merge urban greenery with biologically-active areas of the region, giving up single-function zones, diversifying land use patterns and economic activities in town quarters, developing public transport to restrict the use of private cars in city centres, and locating objects and activities generating mass population movements near public transport nodes.

AN APPROACH INSPIRED BY SYNERGETICS

Synergetics is another theory of the dynamics and structural transformations of complex systems that can be a source of inspiration for the study of the idea of sustainable development. In the course of the discussion about the possible applications of synergetics in empirical sciences (Allen 1994, Weidlich and Haag 1983), many ideas have emerged that can be useful in giving this concept a more operational form. Some of them have been employed in designing the research project on the policy of sustainable urban development whose results are supposed to be of practical use in the formulation of the policy for the city of Poznań. The project rests on the following points.

1. Institutional changes aiming at the elimination of institutional limitations on growth and the creation of growth-stimulating institutions. The changes are supposed to result in new organisational forms of economic activity in the public sector, the creation of a restructuring agency and a foundation for development, links with the gminas (civil parishes) surrounding the city, and the setting up of new organisational units in the city council to deal with, e.g., information, promotion, relations with higher schools and research institutes, relations with partner towns and regions at home and abroad, joint financing, and private-public partnership.

2. Activities of city authorities intended to diversify the city's economic structure. They should seek to vary the structure both in the endogenous (internal, service) sector and the exogenous (external, specialised) one, as well as the links between them. The diversification of the structures can take place through the organisation, or participation in organisation, of new kinds of activities in the domains of technical infrastructure, education, new technologies and products, or business services. The diversifying agent is the development of small and medium-sized enterprises. Some of them combine an earlier handcraft production with the most advanced technology, manufacture goods in small series so as to be able to adjust to the fluctuating demand, and fill new niches on the market where they obtain reasonabale profits. A further development of the structure may take place via expanding economic co-operation with foreign countries. A parallel can be drawn between the diversification of the economic structure and the bio-diversity of the environment.

3. Activities to diversify the city's economic structure can be compared to the use of fertilizers on agricultural soils. A diversified structure becomes more efficient in two senses: it increases its adaptive as well as it creative powers.

4. The market transformation of the economy requires the city and the enterprises and households located in it to adjust to the varying conditions created by fluctuations in the business situation and structural changes. The adjustment is easier if the diversified structure has more economic opportunities to offer.

5. The city's creativity is enhanced by engagement in new fields of activities: information, organisation, coordination, production, services, finance, investment, etc. As a rule, these are higher-quality activities stimulating a rise in the level of technology, organisation and efficiency of enterprises, the qualifications of the human resources, the efficiency of the population's work and incomes, and the performance of urban institutions. Thanks to them the economic structure undergoes further diversification, which in turn stimulates self-reinforcement mechanisms of socio-economic development.

6. An economy with greater adaptive and creative abilities is more efficient. It creates new internal resources and attracts external investors. In such an economy, there may appear relationships and mechanisms described by strongly non-linear and discontinuous functions of demand, production, saving and capital, as well as the strain on and regeneration of the natural environment. The strong non-linearity or discontinuity of these functions create conditions favourable to the structural transformation and sustainable development of the urban economy.

7. The knowledge of these relationships and mechanisms makes it possible to identify control variables that can be used to steer the economy towards effective, innovative and sustainable development (Domański 1995). It also allows for an evaluation of the degree to which they are efficient in attaining the goals of the city's development policy. In other words, it helps to formulate the principles of economic policy. However, both identification and evaluation contain elements of variability, uncertainty and chance which make the pursuit of this policy difficult. Among the objectives set up in the study of urban economic policy, special emphasis is put on its new elements. This is understandable, because it is they that mark the turning points. However, one should not underestimate another operation, viz. modernisation and improvement of its traditional elements. Because of their numerical dominance and the magnitude of the urban resources they concern, they bring the bulk of short-term effects. New elements prove effective only in the long run.

On the basis of this conception, a research project has been devised whose aim is to lay scientific foundations of Poznań's economic policy for the city of Poznań. The project allows for structural transformations and an orientation towards sustainable development of the city economy.

Contrary to common beliefs, the Poznań economy encounters formidable problems in its development, including: an inefficient urban transport system, underdeveloped and decapitalised urban infrastructure, a degraded natural environment, a deep crisis in housing, a low share of advanced technologies, and a deficiency of financial means. The continuation of the present trends would pose a threat to economic vitality and the residents' quality of life, including the quality of the environment.

Poznan's economy also has its strong points and opportunities: the community's high standard of labour and level of economic activity, an advantageous geographical and transport location, an international fair centre, expanding international links, and a dynamic centre of science and culture.

The Poznań authorities have started working on a new development policy that would tend to eliminate the weak points and threats while enhancing the strong points and chances, thus giving the economy a new push. Initial studies have shown that the economic policy of a large city, which is a complex socio-economic, technical and natural system, and one, moreover, that is undergoing a radical systemic transformation, cannot be defined without additional knowledge of the processes taking place in the city and changing its structure. It is also necessary to become acquainted with the most recent trends in the development of large cities in Europe and other comparable regions of the world.

When pursuing the economic policies of large cities in Poland, use is made mainly of earlier practical experience and intuition. In some cases scientific concepts provide a general orientation or a starting point for studies of elements of the urban system. Sometimes they are merely slogans expressing the will to take the direction they indicate. There is a need for an urban economic policy that would rest intentionally on scientific principles and form a consistent system of actions derived from them. The research project submitted below is a step in this direction.

In presenting this project, we start from the assumption that is considered an axiom today, namely that at the close of the 20th and the beginning of the 21st centuries science is going to be a more powerful factor in socio-economic development than today. This assumption refers not only to the role that the existence of a scientific centre plays in the economic development of the city, but also to science-based rationalisation of activities of agents located in the city, including its authorities which should pursue a goal-oriented economic policy.

The Poznań authorities declare in their strategic programme that they will take measures to improve man's environment and steer towards a balanced, modern and open economy, as well as to enhance the city's position as a centre of supra-regional and international significance. In order for these goals to be achieved, the city must pursue an economic policy that will define its internal and external resources, their allocation, scenarios of the city's development and their evaluation, and ways of implementing plans, attracting investors, winning the approval of the local community and solving conflicts. To carry out such a policy, it is not enough to have knowledge deriving from routine statistics and observation of phenomena accessible to everyday experience. It is necessary to know the deeper processes transforming the city's economy, ways of directing them towards the chosen goals, the susceptibility of the processes to such actions, new operation space and opportunity sectors (niches of higher innovativeness and efficiency and weaker competition), ways of choosing the chances offering themselves in this space, and kinds of activities that can set in motion the mechanisms of self-reinforcement and acceleration.

The submitted project defines studies whose results, as the city's deputy president for economic policy declares, will be implemented in this policy to help attain its strategic objectives. By enlarging our knowledge about the city, these results will reinforce the scientific foundations of the economic choice of directions of structural transformation, activities enhancing the efficiency and vitality of the economy, ways of stimulating the creativity of enterprises and the local community, and projects of decisions.

The project is expected to help achieve the following specific goals:

(1) the drawing-up of an analysis of the structural transformation of Poznan's economy in the years 1990-1995;

(2) the defining of the competitiveness of Poznan's economy;

(3) an evaluation of the diversification of the city's economic structure from the point of view of its adaptive abilities;

(4) the elaboration of a concept for a creative city; the identification of non-linear relations and possibilities for stimulating and enhancing the effectiveness of the self-reinforcement mechanism of the city's development;

(5) an improvement of knowledge about the city's metabolism and possibilities for making it develop in an ecologically sustainable way; giving the concept of sustainable development an operational form; and

(6) an improvement in the old instruments of economic policy and the introduction of new ones:

a. new institutional solutions stimulating activity and a growth in efficiency;

b. a policy to diversify the economic structure (budgetary, investment and land policies);

c. microeconomic analysis and policy: endangered enterprises and dynamic and innovative ones;

d. the logistics of creative development (modern technical infrastructure, education, science);

e. the identification of opportunity sectors stimulating the self-reinforcement mechanism and enhancing its effectiveness (promotional policy, technological innovations, multiplier effects);

f. investment, financial and administrative conditions ensuring a constant and exponential rate of improvement in the quality of the natural environment (the period of attaining such a rate, discontinuity points);

g. variants of development scenarios and their evaluation;

h. procedures of implementing development projects; and

i. monitoring the implementation of programmes and the city's development.

The lowest level of detail at which economic analysis and policy will be carried out will be that of single enterprises representing the principal sectors of the economy. From an evaluation of their situation and the wider environment a microeconomic policy will be derived. It will embrace both large and small enterprises, especially those facing difficulties on the one hand and those standing out for their innovativeness on the other.

The city of Poznań and its region Wielkopolska are thought to be areas where development has come the closest to the sustainable model. This belief is shared by representatives of other regions and the central state administration. Some regions set themselves this model as a goal of their programmes. However, it has never been defined in an operational way. A reconstruction of the processes that have shaped Poznań's present economic structure, and keep transforming it, would be highly informative to the authorities of other Polish towns working towards this target. The economic processes observed in Poznań cannot be replicated, of course, but they can be the subject of comparative analyses.

Problems that have appeared recently in the cities of Europe and other regions of the world (deindustrialisation, tertiarisation, globalisation) have given an impetus to the development of scientific disciplines with the city as their subject of research (economic geography, the economics of towns and regions, town planning, urban sociology, and environmental protection). Also, our practical knowledge about city management has accumulated. However, making use of the scientific and practical results in the economic policy of an individual city is difficult for the following reasons: (1) detailed knowledge is scattered; to absorb it all, it would take much work of a specialised scientific team, which the city does not have at its disposal; (2) despite the tendency towards practically-oriented research in world science, there is still a gap between theory and practice which hinders the use of scientific results in designing urban economic policy; and (3) transplanting theoretical concepts and practical experiences of other countries onto Polish soil in a mechanical way is rarely possible. Usually it requires some adaptation and a new contribution calling for high qualifications.

The City Office in Poznań, in co-operation with the city's higher schools, has launched research on the city's new problems which has produced promising results. With the financial support of the Committee for Scientific Research, it would be possible to extend the inquiry and study the problems more thoroughly. The results would provide a scientific basis for the city's economic policy.

The research experience gathered so far shows the following course of inquiry to be feasible: (1) the application of a variety of scientific concepts in building the foundations of the city's economic policy in the various fields of its socio-economic life, and (2) the choice of these concepts which should follow from a broader but consistent scientific construction. By basing many studies on a uniform construction, the scientific foundation of a consistent economic policy will be established. Consistency will facilitate the harmonisation of economic projects and decisions, implemented not only by the city authorities, but also by other agents operating in the city, viz. enterprises and households. This will create conditions in which it will be possible to achieve additional qualitative effects, ones that will require no, or only small, investment outlays.

Such a consistent scientific construction from which principles of an urban economic policy can be derived is supplied by synergetics. Its conceptual apparatus allows an analysis of two processes of transition: (1) from the behaviour of individual agents to the transformation of the urban economic structure, and (2) from one stage of the transformation to another. An analysis of these processes, also at the non-formalised level at which the research is planned, will help identify relationships significant for the definition of instruments that can be used to make the urban system work towards strategic goals. The focus is placed on those relationships that determine the operation of the mechanism reinforcing development and improving its efficiency.

HARMONISATION OF ACTIONS

The efficiency of each policy of transforming the structure and development of the city can be enhanced by the harmonisation of actions. This also refers to the policy derived from the theory of economic development and synergetics. In earlier studies concerned with Poznań's economic policy attempts at harmonisation have been made. They involved: (1) the grouping of the various projects and their connection with objectives formulated in the strategic programme of city development, (2) the delimitation of fragments of the city area in which main investments should concentrate to achieve stronger and more speedy effects, and (3) the definition of the sources of finance of these projects. While these are the right and necessary steps, they do not exhaust all the ways in which actions can be harmonised. The present author has proposed that the projects submitted to the strategic programme should also be viewed from the perspective of: (1) the completeness of actions, (2) their synergy, (3) their sequence, and (4) their spatial harmonisation.

It is an open question whether the strategic goals of the programme form a hierarchical system. The first, general part of the programme does not set up any hierarchy, so I shall pass over this issue. Actions aiming at particular targets have been defined by a competent team of City Office experts, and I assume their list to be given. However, it is worth considering if the list is complete. The completeness, of course, can only be relative, because we have to take account of resource limitations. Thus, given the present and anticipated resources, we have to consider if the set of actions embraces those that are sufficient and necessary conditions of attaining the goals. Next, we have to reflect on the possibility of enhancing effectiveness through synergy, or the joint action of elements of the urban organism in order to mutually reinforce their effects. Further steps in the harmonisation of the programme are establishing the temporal sequence of the most important actions and their spatial harmonisation. The latter task is solved in the course of work on the physical plan of the city by distinguishing key areas, that is, areas of investment concentration. The delimitation of key areas can only be carried out under the tacit assumption of a hierarchy of targets. Since such a hierarchy has not been set up explicitly in the general part of the programme, there is a certain inconsistency there.

In harmonising the actions listed in the strategic programme, a matrix of targets and actions can be helpful. One has been constructed on the basis of actions defined by the City Office. Alterations have been made, however. First, the targets are assigned, not sets of actions, but individual actions, because the former procedure tends to blur actual relations. In fact, all sets of actions are connected with all the targets. The present author has assigned each separate action to the particular targets, thus opening up wider possibilities for their analysis and harmonisation. Secondly, the rows of the matrix presenting the actions and their links with the targets have been moved in such a way as to obtain sets of actions (other than those in the basic version of the programme) grouping actions that appear in the columns (presenting the targets) the same number of times. The frequency with which an action appears in the attainment of the targets can be treated as a substitute for its weight (naturally, each contribution could be weighted, in turn, but this would introduce too much subjectivism from the author).

An ordered matrix of targets and actions (Table 1) makes it easier to answer the questions raised earlier. Thus, do the actions create necessary and sufficient conditions for the accomplishment of the strategic goals? Probably not, despite the multitude of competently matched actions. The completeness of conditions is an ideal to which we can only approximate. Still, it is worth reflecting on it, if only to stop concentrating attention on individual actions and see if some highly significant ones have not been overlooked. Any proposals of new actions must, of course, take into account the limited resources the city has at its disposal.

One of the most significant conceptions of development of modern cities in highly advanced countries is that of creative city logistics. This formulation sums up the most ambitious objectives and tasks. The detailed (second) part of Poznan's strategic development programme contains many elements similar to this conception. However, reflection is needed on the degree of similarity and possible additions. The logistics for a creative city is not likely to develop over those few years for which the present targets and actions are formulated. However, the first strategic programme of the development of Poznań, which is an ambitious city and regarded as such at home and abroad, should accommodate this conception. In the first place, it should be put on the agenda of the city authorities and services, and then the implementation of the programme should be purposefully directed in such a way as to make the actions undertaken today the first steps towards the goals set by this conception. They will include the development of modern telecommunications, banks, insurance companies, consulting agencies and other firms creating the business environment. The creativity of the local community and the economic sector will be enhanced by investment in human capital as well as research and development.

What conclusions about synergetic effects can be drawn from the matrix of targets and actions? To answer this question we must first identify the bundle of especially important actions, i.e. ones that are necessary to attain the greatest number of targets. Next we have to look for the possibility of co-operation among them to heighten the effects. The bundles of particularly important actions are fairly easy to discern. In the matrix they are encircled with a solid line (important ones with a thin one, very important with a thick one). These are actions aiming at: (1) environmental protection, in particular the improvement of water management, (2) the building of new (and extension of old) technical infrastructure (a motorway, telecommunications, areas of higher schools, modernisation of the railway node, the fast tram, etc.), and (3) the development of higher-order supra-local services (the Poznań International Fair, economic information, technological policy, the World Trade Centre, promotion of the Poznań economy, co-operation with Polish and European cities, the airport, etc.). The harmonisation of these actions should be facilitated by two further actions of fundamental significance: the city's master physical plan and steps towards qualitative development of its economy, which are the core of the strategic programme. High on the importance list are also actions concerning the land economy and utilities as well as social and cultural matters. The distinguished bundles of actions form a pattern that conforms to the principles of urban economics. Thus, on the one hand we have endogenous (internal) functions (focusing on the needs of the city itself: environmental protection, infrastructure) and on the other, exogenous (external) ones (those deciding about the city's development: higher-order services). Endogenous functions should create the logistics for the expansion of exogenous ones. Hence, they should be coupled.

The team of City Office experts can distinguish pairs or larger sets of actions in which synergetic effects can be produced. These sets should be given special attention and support by the City Office. For example, synergetic effects can be expected from the following combinations of actions:

1. Supporting the development of higher schools, trade information and sectoral information centres, technological policy, a technological park and an incubator of enterprise in the sphere of biotechnology. Biotechnology has very good conditions for development in Poznań. They are created by the scientific potential of the Institute of Bio-organic Chemistry of the Polish Academy of Sciences, various institutes of the Adam Mickiewicz University and the Agricultural Academy, and other scientific institutions. The City Office could start work on this bundle by inviting the co-operation of Poznań's scientific and industrial circles, the Committee for Scientific Research, the Ministry of National Education, the Ministry of Industry and Trade, and institutions managing foreign aid.

2. Another bundle of actions can be started with telecommunications, a motorway, an airport, a modernised railway station, and recreation grounds (logistics), to be followed by: the Poznań International Fair, a congress centre, initiatives in the spheres of culture, sport, the hotel industry, and European studies (higher-order service functions).

3. There are germs of yet another bundle of actions in the role that Poznań plays already in territorial and economic self-government. It may be well, therefore, to cultivate and develop them. The following actions are involved: strengthening the already established contacts among self- government institutions at home and abroad, creating institutions to serve these contacts (the organisation of seminars and conferences, the editing of publications), creating infrastructure for them (possibly as part of the congress centre project), supporting scientific work on local and regional problems, and providing services in this domain for towns and communes of north-western Poland.

4. Further bundles can be sought in the relations between the surroundings and niches of attractiveness in the city economy.

Let us now pass on to a brief discussion of the sequence of actions in time and their spatial co-ordination. In the first case, harmonisation should be based on drafts of technical designs; in the other, it is attempted right now, in the course of work on Poznań's master physical plan.

The sequence of steps should take into account the investments and other activities which the city has already begun and wants to complete, as well as the limited means at its disposal. Defining the sequence does not mean that actions are to be ordered one after another (the second starts after the first has been completed, etc.). Many actions should be pursued simultaneously. It is fairly obvious, however, that the temporal sequence should begin with: investments in progress (e.g., the fast tram), low- budget enterprises (e.g., information, technological policy), measures against degradation processes in the city (e.g., water pollution, municipal waste, traffic congestion in the centre), and actions of particular importance for increasing the city's dynamics, especially for making its development qualitative (e.g., a motorway, the modernisation of the railway station, telecommunications).

The choice of three key areas (the centre, the fast tram route and its surroundings, and the Lake Malta area) seems to me to be judicious. The City Office team of experts should consider the possibility of distinguishing a fourth key area, under the name of "The expansion of commercial and service facilities in city quarters. New job opportunities in city quarters". The continuation of activities in this field should be backed up by land, rent and tax policies. Without this continuation, the problem of traffic congestion in the centre will be impossible to solve. In activities pursued in urban areas, hierarchical thinking can be observed, long known to urban economists and city planners. In the city centre only those activities should be encouraged that require a central location. At the same time, those activities that do not have to be located there should be gradually wound up. One of the ways to limit them is the improvement of access to shops and services in city quarters and on housing estates. Stimulating the commercial-service sector in these places would, moreover, open up new job opportunities, which would redress the spatial imbalance between places of work and places of residence, thus eliminating some of the strenuous journeys to work. This action need not engage municipal means. It is mainly a question of regulation.

What raises reservations in the assumptions of the city's physical plan is the basic conception on which the urban structure rests. The city has been divided into three zones: the centre, an intermediate zone, and an external-contact one. One can trace here the influence of the concentric or ring conception (Burgess' model). At a guess, this conception has been used as a result of the assumption that the city will go on developing within the existing administrative limits by utilising free building sites and the modernisation of the building-up (a compact city). This assumption need not be questioned, since it seems a reasonable directive for action in the period of transition. However, the conception of a concentric or ring arrangement does not follow inevitably from that of a compact city. Presumably, it is related to, or influenced by, the conception of the transport system. This, however, is an important, but not sole, criterion of demarcating and shaping the city's spatial structure, which is a multi-dimensional system. Apart from the concentric or ring pattern, it is composed of sectoral elements and multi-centre patterns. The zoning pattern, as presented in the assumptions of the physical plan, is a pictorial description of a future city, but is obviously not meant to be a tool for shaping its spatial development.

Multi-centre patterns can also form without the city expanding beyond its present administrative limits, especially when the centres (sub-centres) are considered as concentrations of activities, and not only of patterns of permanent building-up. Multi-centre patterns are, naturally, more characteristic of urban agglomerations. They will also develop in the environs of Poznań as a result of socio- economic processes the city does not control fully. Still, stopping the city from sprawling is a target during the period of transition, although it can only be pursued within the competence of the city authorities. Spontaneous processes will develop inevitably and the sprawl is bound to take place. It may be worthwhile, therefore, to try to control them by building up co-operation with the surrounding gminas. In the first stage, a common study of the physical and socio-economic development of the Poznań agglomeration should be made. It might prevent so-called defective urbanisation, among other things.

THE NEED FOR MEASURING ECOLOGICAL-ECONOMIC RELATIONS

The relations binding elements of ecological systems as well as these systems with economic ones should not merely be given a verbal description, but should also be quantified, if possible. In a quantified form, they can be processed further using mathematical methods, thus providing additional information and helping to solve problems that are insoluble in any other way. The quantification of economic relations is fairly advanced, and keeps developing. There are statistical data on economic relations in abundance, but first attempts at quantifying ecological- economic relations have first been made only recently, within the domains of both ecology and the economy, by extending the ecological approach to cover the economy and the economic approach to cover ecological issues.

In the economy, an attempt was made using the well-tried input-output models. We owe their conception to W. Leontief, and its regional extension to W. Isard (1969). They are an efficient instrument for the description of regions and regional systems. Each region has a structure of its own, and its elements include, e.g., the economic sectors. A regional table of intersectoral flows can be transformed into a table of input-output coefficients. Its construction is extremely labour-consuming, which is why not many have been made to date. One of the first in the world was that constructed for the region of Philadelphia.

The coefficients define the input of one product or service necessary to produce a unit of another product or service in the given region. In the region of Philadelphia, it takes $0.148 worth of agricultural and fishery products to obtain a foodstuff of $1 worth, and $0.027 worth of chemical products to produce a $1-worth textile product.

Once we have an input-output table and an inverse matrix of coefficients calculated on the basis of it, we can quickly solve various analytical and planning problems. For instance, we can answer a question as to what quantities should be produced by the particular sectors in the given region when the supplies to other regions (the outflow) change in a specified way. In other words, we can quickly prepare several variants of the production programmes for the particular sectors in the region depending on what magnitude of supplies we expect to go to other regions. Once we know the output by sector, we can also determine internal flows in the region, that is, mutual supplies among enterprises located on its territory.

When purely economic models turned out to be insufficient and ecological factors started to arouse interest, the input-output tables were extended to include coefficients expressing the flows of commodities between the economy and the environment, i.e., between the economic and the ecological system. The assumptions on which this procedure rested were that the ecological system, like the economic one, could be considered in terms of the input-output method, and that both systems could be linked sensibly, to the extent in which the import of one was the export of the other, and the other way round (Isard et al. 1969). In order to include additional relations, the matrix of coefficients should be enlarged (Fig. 1). Thus, to the left-hand upper block representing the familiar coefficient table for the economic system is added a right-hand lower block, which is a coefficient table for the ecological system, as well as a left-hand lower and a right-hand upper block containing the coefficients representing flows from the ecological to the economic system and vice versa.

		ECONOMIC ACTIVITIES						ECOLOGICAL PROCESSES				
		Agriculture	Textile Industry	• • •	Petroleum refining	• • •	Sport fishing	• • •	• • •	Plankton production	Herring production	Cod production
ECONOMIC COMMODITIES	Wheat											
	Cloth											
	• • • • • •			ECONOMIC SYSTEM: INTERSECTOR COEFFICIENT				ECOLOGICAL PROCESSES: THEIR INPUT AND OUTPUT COEFFICIENTS RE ECONOMIC COMMODITIES				
	Crude oil											
ECOLOGIC COMMODITIES	Water intake											
	Alkalinity											
	• • • • • •			ECONOMIC SECTORS: THEIR INPUT AND OUTPUUT COEFFICIENTS RE: ECOLOGICAL COMMODITIES				ECOLOGICAL STSYSTEM: INTER-PROCESS COEFFICIENT				
	Plankton									+	—	
	Herring										+	—
	Cod						—					+

Fig. 1. Matrix of coefficients for the economy-environment system (acc. W. Isard et al. 1969)

Worth noting are the new types of coefficients found in the enlarged matrix. Let us take the oil-refining industry as an example. In the course of production, it uses both economic and ecological commodities. To produce an output of $1 worth, refineries spend, say, $0.612006 on oil and $0.089378 on labour. These coefficients should be entered in the left-hand upper block, in the 'petroleum' row and the 'petroleum refinery and processing' column. Right now, however, we are interested in the ecological commodities that the refineries take from the environment. One of them is water. Its use by the oil industry can take a variety of forms: water intake (for production, cooling and sanitary purposes) or water pollution with waste. The inputs

TABLE 1. Matrix of targets and actions

Position in strategic programme	Actions	Target 1	Target 2	Target 3	Target 4	Target 5
		Healthy environment	Efficient urban organism	Modern economy	International importance	Supra-regional importance
	Actions aiming at four targets					
3	Purity of streams	IA3	IA3	IA3	IA3	
6	Treatment plant, sewerage and heat distribution network	IA6	IA6	IA6	IA6	
9	Water supply to city	IA9	IA9	IA9	IA9	
10	Municipal waste management	IA10	IA10	IA10	IA10	
14	Master physical plan	IB1	IB1	IB1	IB1	
34	Qualitative aspects of economic development		IIA1	IIA1	IIA1	IIA1
41	A-2 motorway		IIE3	IIE3	IIE3	IIE3
53	Recreation grounds	IIID3		IIID3	IIID3	IIID3
54	Telecommunication connections		IIID4	IIID4	IIID4	IIID4
56	Development areas of higher schools		IIIE2	IIIE2	IIIE2	IIIE2
62	Modernisation of railway node		IVA6	IVA6	IVA6	IVA6
64	Poznań Fast Tram		IVB1	IVB1	IVB1	IVB1
66	Lake Malta surroundings	IVC	IVC		IVC	IVC
	Actions aiming at three targets					
1	Air quality	IA1		IA1	IA1	
5	Pro-ecological behaviour	IA5	IA5		IA5	
18	Spatial-visual zone	IB5			IB5	IB5

20	Housing	IC1	IC1	IC1		
21	Council housing	IC2	IC2	IC2		
23	Public health care institutions	ID2	ID2			ID2
27	Continuation of cultural activities	IF1			IF1	IF1
28	Cultural initiatives	IF2			IF2	IF2
30	Sporting events	IG1			IG1	IG1
35	Commercial information			IIA2	IIA2	IIA2
36	Sectoral information centres			IIA3	IIA3	IIA3
37	Co-operation with local government			IIB1	IIB1	IIB1
38	Technological policy			IIC1	IIC1	IIC1
39	Poznań International Fair			IIE1	IIE1	IIE1
40	World Trade Centre			IIE2	IIE2	IIE2
43	Image of Poznań city			IIIA1	IIIA1	IIIA1
44	Participation in fairs			IIIA2	IIIA2	IIIA2
45	Information about Poznań			IIIA3	IIIA3	IIIA3
46	Promotion publications			IIIA4	IIIA4	IIIA4
47	Co-operation with towns		IIIB1	IIIB1	IIIB1	
49	International self-government organisations		IIIC1	IIIC1	IIIC1	
50	Local governments in Poland		IIIC2	IIIC2		IIIC2
51	Airport		IIID1	IIID1		IIID1
52	Hotel trade			IIID2	IIID2	IIID2
57	City hall		IVA1		IVA1	IVA1
58	Historic Fara parish church		IVA2		IVA2	IVA2
59	Oldest parts of city		IVA3		IVA3	IVA3
60	Cultural, trade and sporting events			IVA4	IVA4	IVA4

involved can be presented as coefficients. Cooling water costs \$0.114861, e.g. per \$1 of output. Inputs involved in the use of land and air can be calculated in a similar way.

Another sector of the economy, connected with the natural environment even more closely, is recreational activity. Among its various forms is sport fishing. In the already quoted work by Isard et al., the input-output method is employed to study sport fishing in the Plymouth Bay in New England. The chief fish species there is the cod. Empirical studies show that in order to produce the recreational effect, motor-boat fishing should give 6,200 pounds of cod per 1,000 man-days. We enter this figure in the cell of the coefficient table corresponding to the 'cod' row and the 'sport fishing' column.

The cod is an outcome of the production process occurring in the ecological system. As a result of biological studies, it has been established that the following inputs are necessary to produce 1 pound of cod: 1.167 pounds of herring, 1.167 pounds of small fish, and 8.333 pounds of carnivorous invertebrates. In turn, to produce 1 pound of herring it takes 10 pounds of plankton, and 1 pound of roach and carnivorous invertebrates, 10 pounds of herbivorous invertebrates. All these processes are links of the food chain in the ecological system. Their input-output data can be entered in the right-hand lower block of the table: production processes in columns and the inputs in rows.

The attempts at giving the idea of sustainable development an operational character impose higher information requirements. The stock of information gathered and processed so far should be extended to cover, e.g. the data on urban (or wider, regional) metabolism.

When applied to the urban economy, the term 'metabolism' means the transformation of urban resources in a way that enables this economy to perform its functions, i.e., the production of goods and services, the satisfaction of needs of the local community, and co-operation to sustain and develop the rest of the socio-economic and spatial systems (that is, the regional, the national and the global system, depending on the city's economic potential). For its metabolism to work efficiently, the city has to create suitable technical, economic and social structures. Gaining insight into urban metabolism is important in many ways. It reveals relations among the particular components of the urban economy and makes possible the reconstruction of processes taking place in the city's development; hence, it also helps determine the ways of influencing those processes to make them work towards the stated social aims. Attempts to apply the idea of sustainable development will require a fuller examination of the city's natural environment, the relations holding between it and the city's economic development, and requirements which have to be met for economic development, the improvement in the quality of the environment, and the legacy of decent environmental conditions to future generations to be possible. One of these requirements is the reduction in the consumption of raw materials and energy per unit of production and income (dematerialisation of production).

CONCLUSIONS

For the idea of sustainable development to change from an attractive slogan into a tool of ecological and economic policies, it must be given an operational form. This should make it possible to derive from it actions that will help transform economic systems in a pro-ecological way. The actions should be economically feasible and socially acceptable.

The present author suggests two approaches to the task of making the idea of sustainable development operational. The first is inspired by the theory of economic development, the other by the theory of synergetics. The theory of economic development is helpful because it formulates conditions for reforging the economic mechanism and giving the economic system a big push. Synergetics, in turn, helps define the transition from micro-scale changes to macro-scale ones, and then the mechanism of transition of complex systems from one level of complexity to another. Thus, it can also be useful in the study of structural transformations of ecological-economic systems.

In the author's opinion, one of the necessary conditions of making the idea of sustainable development operational, is the enlargement of the stock of information about the relations holding among elements of ecological systems, and between those systems and economic ones. The conceptual basis for building up and processing new stocks of information can be provided by the models of intersectoral and interregional flows and the model of metabolism of cities and regions.

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