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^{14}C DATES OF PEAT FOR RECONSTRUCTION OF ENVIRONMENTAL CHANGES IN THE PAST

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Abstract: Cumulative Probability Density Functions (CPDF) for sets of ^{14}C dates of peat were constructed for different geographic regions of Poland. On the preliminary stage of our study, CPDF for Southern Poland region seemed to be in good correlation with appropriate distribution for Lowlands and Lake Districts region, but rather in anticorrelation with Baltic Coast region. Similarly, CPDF for Baltic Coast region and Lowlands and Lake Districts region seemed to be in anticorrelation. Authors made Monte Carlo experiment to estimate significance of correlation coefficient value. The amount of dates in analysed sets is too low to draw unequivocal conclusions.

1. INTRODUCTION

Since the fifties the radiocarbon dating has become a standard tool for Quaternary geologists and archaeologists, as well as for specialists involved in studies of environmental processes. Majority of samples dated in Gliwice Radiocarbon Laboratory came from the territory of Poland. They are regarded as physical data, and elaborated statistically, with a special emphasis on their properties related to the past environmental and climatic changes. Since the seventies an analysis of frequency distribution of ^{14}C-dated samples in a time scale has been carried out for several selected geographic regions (e.g. Geyh and Streif, 1970; Geyh, 1971; Geyh and Rhode, 1972; Geyh and Jakel, 1974; Geyh 1980; Pazdur and Pazdur, 1986; Goździk and Pazdur, 1987, Michczyńska *et. al*., 1996). The radiocarbon dating method, which was primarily used simply to determine age of sediment containing dated samples, became an important source of information on the course of some geologic processes in the past.

2. METHODS

The result of radiocarbon dating is given as measured radiocarbon age T and its laboratory uncertainty ΔT. A lot of independent factors (such as fluctuations of cosmic ray flux, atmospheric pressure, humidity etc.) affect the results of measurement. In this situation repetition of measurement gives different results for each case, but these results are subject to specified statistical rules, well described by Gauss probability distribution. The width of Gauss curve depends on uncertainty value – the higher value of uncertainty wider the curve. Result of radiocarbon measurement: $T \pm \Delta T$ – means that real age of dated sample does not differentiate from result of measurement by more than ΔT with 68% probability. The probability density function of Gauss distribution is described by equation:

$$p(\tau) = \frac{1}{\sqrt{2\pi}\,\Delta T}\cdot \exp\left[-\frac{1}{2}\left(\frac{\tau - T}{\Delta T}\right)^2\right], \tag{2.1}$$

where τ is the real radiocarbon age of sample.

For a set of radiocarbon dates for specified type of deposits and dates cover considerable range in time and area we calculate the cumulative probability density function CPDF by summing normal distributions connected with particular dates. The cumulative probability density function is shown by equation:

$$f(\tau) = \frac{1}{\sqrt{2\pi}\,N}\cdot \sum_{i=1}^{N}\frac{1}{\Delta T_i}\cdot \exp\left[-\frac{1}{2}\left(\frac{\tau - T_i}{\Delta T_i}\right)^2\right], \tag{2.2}$$

where: T_i and ΔT_i are respectively age and uncertainty of i-sample and N is number of all dates. The graph received in this way has characteristic peaks and gaps. An idea of constructing of cumulative probability distribution for a few exemplary ^{14}C dates is presented in **Fig. 1**.

An interpretation of CPDF is based on two basic assumptions:

1. The number of ^{14}C dated samples is proportional to the amount of organic matter deposited in sediments in considered time interval.
2. The amount of organic matter in sediments depends on palaeogeographical conditions.

3. INTERPRETATIONS PROBLEMS

When the criteria for including ^{14}C dates in an analysed set are chosen suitably, fluctuations of constructed distribution reflect the interference of changes of the investigated phenomenon (archaeologic or geologic), otherwise they can have other reasons (Stolk *et al.*, 1994):

An insufficient number of ^{14}C dates

Statistical evaluations relating to numbers of required ^{14}C dates were presented by Geyh (1980). Let's consider the set of N ^{14}C dates, where σ denotes the average standard uncertainty of the dates. When the data set is considered as a random population, dates are uniformly distributed over all the whole time range T. The time range T can be divided in so-called class intervals. The width of class interval equals 2σ. The probability p that selected date belongs to a certain class interval is constant and equal $p = \frac{2\sigma}{T}$. The probability that in considered class interval there are n dates is described by binominal distribution. This distribution transforms into Poisson distribution for large value of N. In such situation expected value of n – $E(n)$ and dispersion $D(n)$ are described as follows:

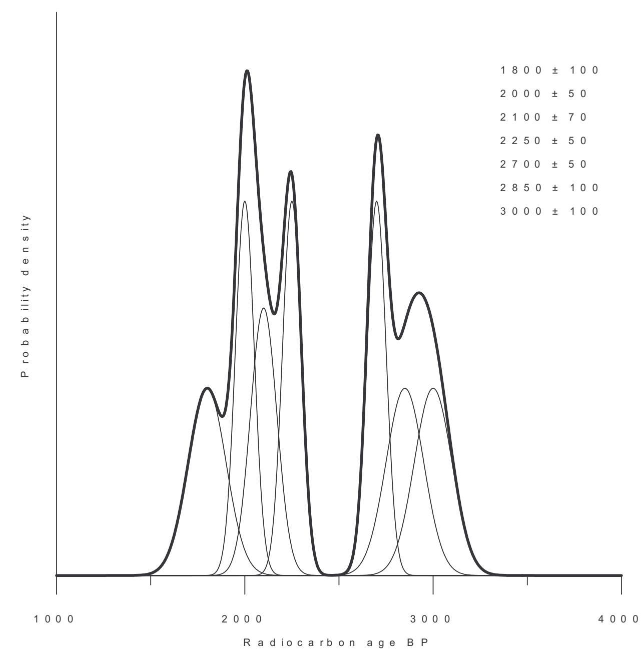

Fig. 1. *An example of construction of cumulative probability density function CPDF for 7 listed ^{14}C dates.*

$$E(n) = \frac{2\sigma N}{T} = z \tag{3.1}$$

$$D(n) = \sqrt{\frac{2\sigma N}{T}} = \sqrt{z} \tag{3.2}$$

where z is called population density, and statistical fluctuations s as:

$$s = \frac{D}{E} = \frac{1}{\sqrt{z}} = \sqrt{\frac{T}{2\sigma N}} \tag{3.3}$$

Geyh (1980) proposed two limits of s value: ±20% (what corresponds to z=25) and ±50% (z=4). According to these limits there should be a minimum 4 dates per class interval, and more than 25 dates per class interval in order to get reliable results.

Preferential sampling

Overinterpretation of certain periods or areas may be due to preferential sampling (Geyh, 1980; Goździk and Pazdur, 1987; Stolk *et al.*, 1994). Samples for ^{14}C dating are frequently collected only from selected horizons, which are of special interest from the point of view of investigator, or from levels of questionable age. This practice seems to be a general rule in studies of outcrops or cores rich in organic deposits because of economic reasons (limited funds for dating). Studies focused on small regions may cause serious deformation of CPDF because of dominating local effects.

Only critical selection of ^{14}C dates used for construction CPDF can eliminate errors caused subjective sampling.

Non-linearity of the radiocarbon time scale

The non-linearity of radiocarbon time scale may results in clustering of ^{14}C dates. CPDF may show maxima or minima that are not at all related to geologic events. Fluctuations of the distributions resulted by non-linearity of the ^{14}C scale can be eliminated by probability calibration of these distributions (Pazdur and Michczyńska, 1989; van der Plich and Mook, 1989; Michczyńska *et al.*, 1990). Another method of solution this problem was discussed by A.D. Stolk *et al.* (1989).

Törnqvist and Bierkens (1994) are pointing that the choice of the degree of smoothing of calibration curve is an important step. According to this authors high-resolution calibration curve may be used only for highly precise and accurate dates. **Fig. 2** presents influence of calibration curve's smoothing degree on the shape of CPDF constructed for 539 ^{14}C dates of peat. Dated samples came from the territory of Poland. Calibration curve is replacing by cubic spline function, calculated according to the procedure of Reinsch (1967, after van der Plicht and Mook, 1989). The calculations is performed iteratively such that:

$$\sum_i \left[\frac{(y(x_i) - y_i)}{\sigma(y_i)}\right]^2 \leq S \tag{3.4}$$

where S is the smoothing parameter, and the function $y = f(x)$ represents the calibration curve. It is evident

(**Fig. 2**) that degree of smoothing has not influence on the main peaks and gaps. In the case when only the global changes are subject of investigations the degree of smoothing does not play important role. For our further analysis we choose calibration curve with smoothing parameter equal 100 yr.

Decreasing availability of older deposits

Younger deposits, which as a rule lie near the present surface, can be found more frequently than the older ones. This leads to obvious tendency that the older the samples the more decreasing frequency of ^{14}C dates. Moreover older ^{14}C dates are subjected to greater measurement uncertainties because of purely statistical reasons, what influences the shape of CPDF. So higher peak on the CPDF graph must not mean better conditions favourable for sedimentation of specified type of deposit.

In statistical analysis of CPDF of ^{14}C dates following facts should be taken into account, too:
– different type of deposits should be analysed separately,
– ^{14}C ages should be corrected considering "hard water effect" (e.g. gyttja, lake deposits),
– ^{14}C ages for samples which seem to be contaminated with younger or older organic matter (e.g. disagreement ^{14}C age with pollen analysis) should be eliminated.

4. ANALYSED MATERIAL

About 540 radiocarbon dates of peat from Poland were selected for statistical analysis. All the dates came from Gliwice Radiocarbon Laboratory. Peat is a typical organic material, often dated using ^{14}C method. Received radiocarbon ages are reliable and do not require correction because of "hard water effect" or isotopic fractionation (Pazdur, 1982). These facts decided that this type of deposit was chosen for analysis. Analysed dates come from the mires where peat occurs up to the roof or is covered by different formations less than 50cm thickness. None of mires was preserved from before the last glaciation, so analysis is limited to the Holocene and Late Pleistocene. Locality of sampling sites is presented in **Fig. 3**, where the boundaries of geographical lands were marked too. Numbers of sites and ^{14}C dates for each geographical land are shown in **Table 1**. Only for 396 dates detailed information was given about sample's position within investigated profile therefore at this stage of our study we assume that sampling strategy doesn't dis figure analysed frequency distributions.

In **Fig. 4** CPDF of ^{14}C dates for 3 geographical regions of Poland are presented. Because of insufficient amount of ^{14}C dates (amount of dates per class interval ≈ 2 for Baltic Coast and Southern Poland, and ≈ 3,7 for Lowlands and Lake Districts) these distribution are not fully reliable from statistical point of view, but even in this situation some general conclusions can be drawn. It may be expected that CPDF of dates from Southern Poland would be better correlated with appropriate distribution for

Table 1. *Number of sites and ^{14}C dates versus geographical lands.*

Geographical land	***Number of sites***	***Number of ^{14}C dates***
Baltic Coast	48	138
Lake Districts (together)	78	186
a. Pomeranian	25	63
b. Masurian	41	37
c. Great Poland	12	86
Lowlands	52	91
Uplands	14	59
Subcarpathians Basins	11	27
Mountains	22	48
Together	225	549

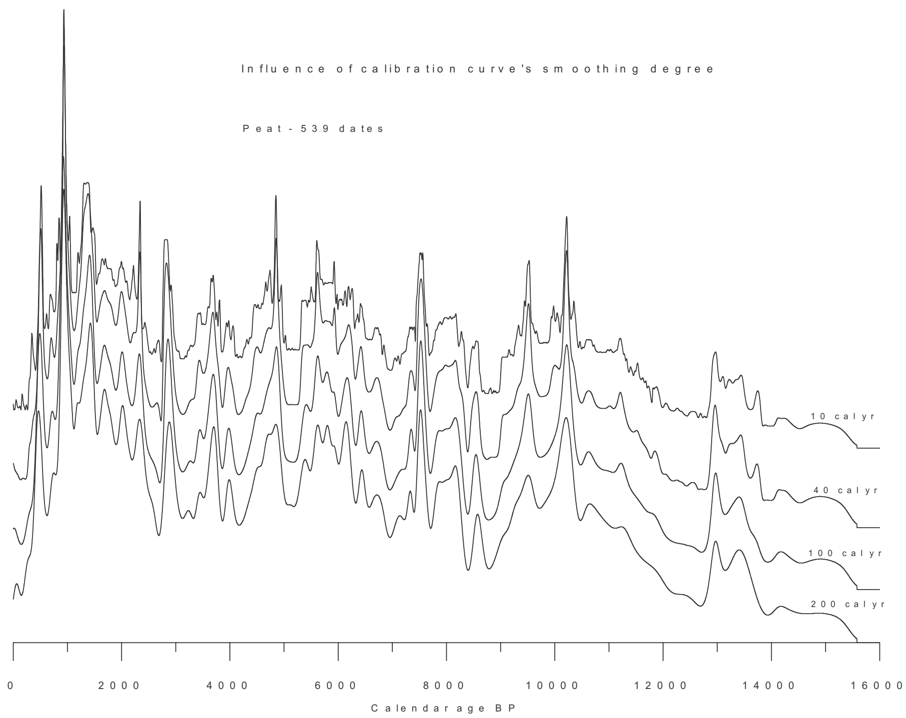

Fig. 2. *Influence of calibration curve's smoothing degree on the shape of CPDF. The distribution is constructed for 539 dates of peat's samples from the whole territory of Poland. Values of calibration curve's smoothing degree are given in calendar years. Details of smoothing procedure were described by J. van der Plicht (1993).*

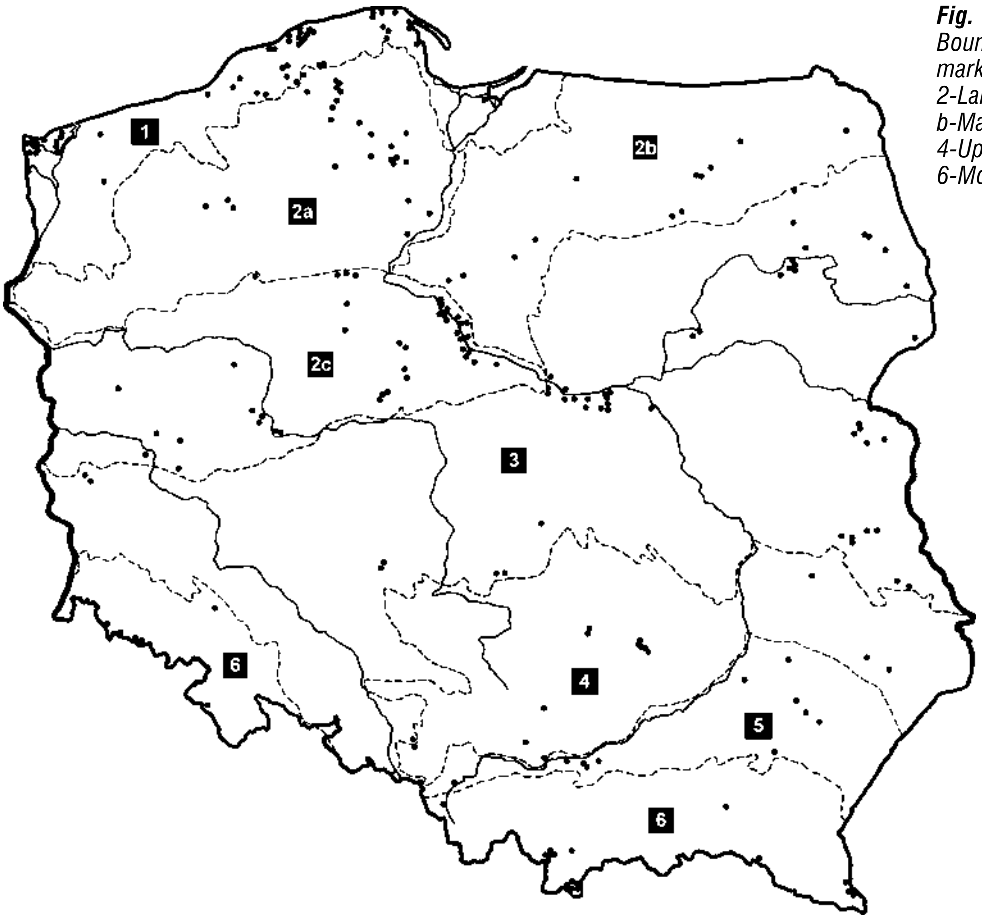

Fig. 3. *Localization of sampling sites. Boundaries of geographical regions are marked by dashed lines. 1-Baltic Coast, 2-Lake Districts: a-Pomeranian, b-Masurian, c-Great Poland, 3-Lowlands, 4-Uplands, 5-Subcarpathians Basins, 6-Mountains.*

Lowlands and Lake Districts than with distribution for Baltic Coast, because of geographical situation of these regions. The CPDF distributions presented in **Fig. 4** seem to confirm this supposition, but in order to check our expectation more precisely we calculate correlation coefficients between particular distributions. Value of correlation coefficient assigned on graph to calendar age x - **CC(x)** was calculated according to formula (4.1):

$$CC(x) = \frac{\sum_{i=x-500}^{x+500} (P_A(i) - E_A)(P_B(i) - E_B)}{\sqrt{\left[\sum_{i=x-500}^{x+500} (P_A(i) - E_A)^2\right]\left[\sum_{i=x-500}^{x+500} (P_B(i) - E_B)^2\right]}}$$

where P_A and P_B – intensity of frequency distribution A and B, E_A and E_B – mean values of $P_A(i)$ and $P_B(i)$ in the range of sum. We chosen summing range for correlation coefficient 1000 years arbitrarily. Different methods of CC(x) calculation will be an object of further consideration. In this study we tested possibilities of such method of distributions comparing. Values of these coefficients between CPDF for Baltic Coast and for Southern Poland, for Baltic Coast and for Lowlands and Lake Districts, for Lowlands and Lake Districts and for Southern Poland are presented in **Fig. 5**. Sudden changes of sign of these coefficients are characteristic for all graphs. Correlation coefficients reach relatively great absolute values for most of time ranges. In order to attain better representing of correlation and anticorrelation range's the sign of correlation coefficients was presented in **Fig. 6**. The correlation coefficients were calculated in 1000 years intervals, so only general dependence is shown.

To decide question if observed correlations or anticorrelations are real and result from environmental processes or they are only results of probability distributions fluctuations caused by insufficient amount of dates in analysed sets we made Monte Carlo experiment. We assumed that distribution of dates on the calendar time scale is uniform. Succeeding stages of experiment comprised:

1. Random generation of N_i dates from the range 0-16 kyr cal BP (N_1 = 135 dates, N_2 = 272 dates, N_3 = 132 dates).
2. Finding of N_i radiocarbon dates corresponding to N_i calendar dates.
3. Calibration of N_i ^{14}C dates. We assume same value of uncertainty, equal mean laboratory uncertainty in analysed date's sets, for all generated dates.
4. Calculation Cumulative Probability Density Function (CPDF).
5. Repeating items 1-4 for another N_i value.
6. Calculation of correlation coefficient between two CPDF.
7. Repeating items 1-6 ten thousands times.
8. Estimation of 50, 70 and 90% confidence intervals.

Calculated confidence levels are marked in **Fig. 5**. For **Fig. 5a** and **Fig. 5b** statistically important anticorrelation for range ca. 9-10 kyr cal BP is visible. For **Fig. 5b** there is once more time range of visible anticorrelation – ca. 4-5 kyr. For **Fig. 5b** there are distinct, long time ranges, where *CC* attains negative values (cf. **Fig. 6b**), but values of *CC* do not let us to draw unmistakable conclusion, that observed anticorrelations are not accidental. Although for correlation coefficient between Lownalds and Lake District and Southern Poland attains positive values for long time intervals (cf. **Fig. 6c**), results of Monte Carlo experiment point out, that primary hypothesis about correlation is unconfirmed.

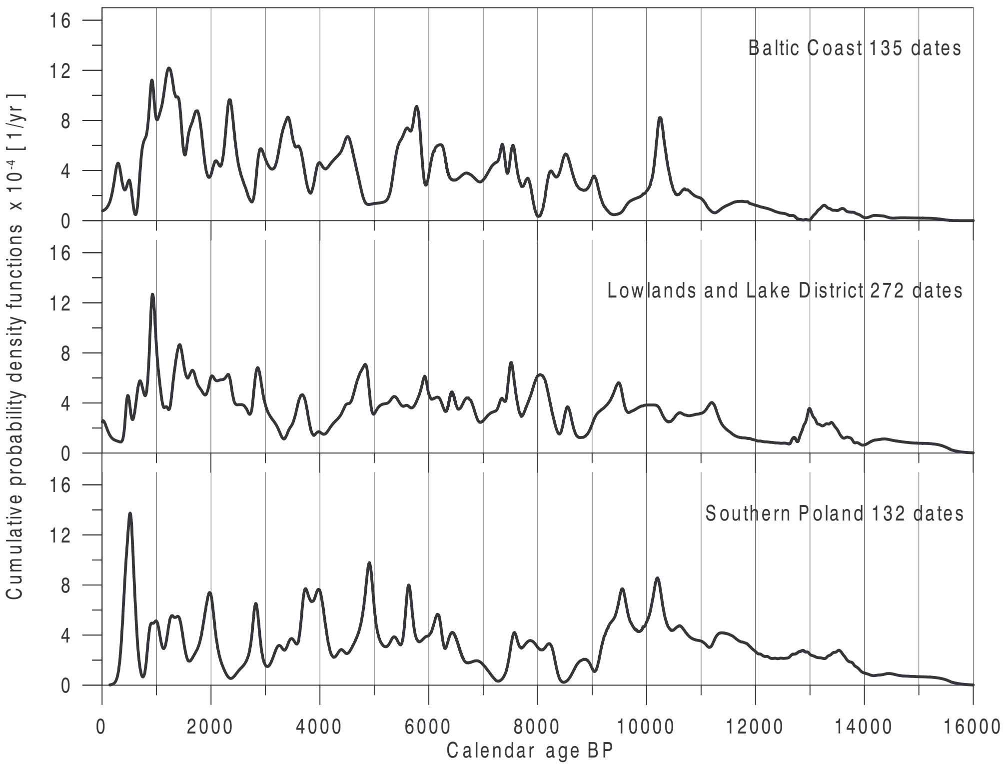

Fig. 4. *Cumulative probability density functions CPDF of ^{14}C dates for 3 geographical regions of Poland.*

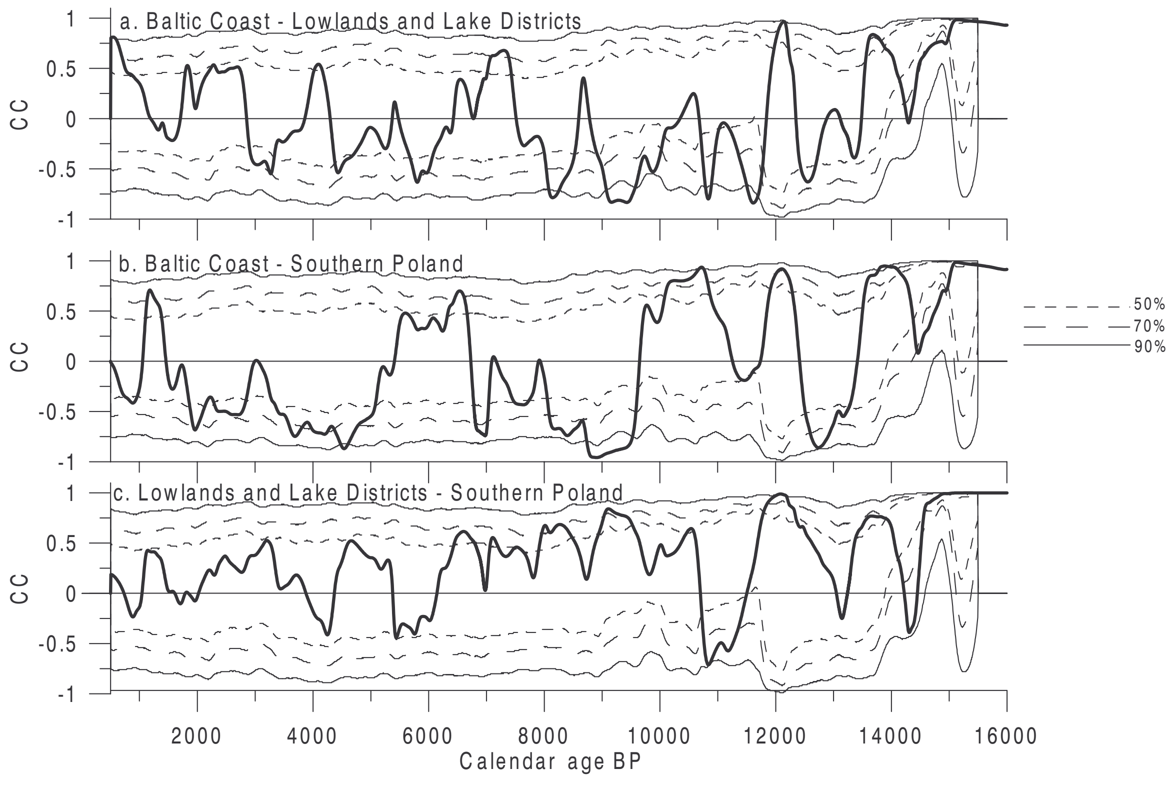

Fig. 5. *Values of correlation coefficients between CPDF of ^{14}C dates for Baltic Coast and for Southern Poland, for Baltic Coast and for Lowlands and Lake Districts, for Lowlands and Lake Districts and for Southern Poland bold line. Confidence levels 50, 70 and 90% are drawn different kinds of curves (as marked).*

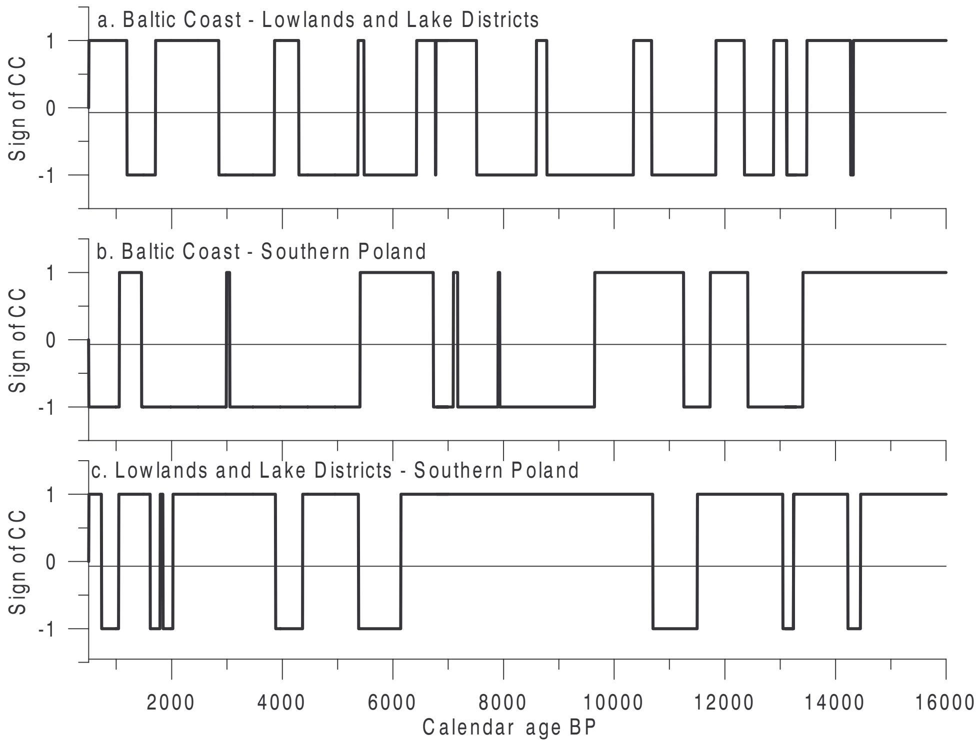

Fig. 6. *Sign of correlation coefficients presented in Fig. 5.*

CONCLUSIONS

Results of many studies suggest usefulness of statistical analysis of radiocarbon data for reconstruction of environmental changes in the past. In this article authors try to establish criteria of comparing probability density distributions. In the light of realised Monte Carlo experiment, assumed by author's dependencies between probability density distributions of ^{14}C dates for different Polish geographic regions require verification. Authors' forthcoming research, in the field of reconstruction of time scale for environmental changes during the Holocene, is to be focused on exploiting of statistical methods for analysis of large sets of ^{14}C dates from various geographical regions. Firstly, authors are intending to repeat experiment basing on bigger sets of ^{14}C dates and estimate how number of dates affect significance of correlation coefficient value. Gliwice Radiocarbon Data Base requires supplement based on literature sources because of lack of detailed information about dated samples in Sample Information Sheets. Detailed information about dated samples will let us to verify if sampling strategy disfigure examined probability density distribution, or not.

Presented in this article CPDF of ^{14}C dates were made using properly modified Gliwice Calibration Programme GdCalib. Only distributions for different smoothing parameter were calculated using CALHIS program – an option in the Groningen ^{14}C calibration program (van der Plicht, 1993).

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