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STATISTICAL ANALYSIS OF RADIOSONDE MEASUREMENTS OF WIND SPEED IN POLAND

Radiosonde measurements of wind speed at three stations belonging to the Institute of Meteorology and Water Management (Legionowo, Łeba and Wrocław) in a 5 year period (1991–1995) were analysed, using the method reported in *European Wind Atlas* [22]. The frequencies of wind vector components on 5 levels (up to 200 m above the ground level) and the parameters *A* and *C* of the Weibull statistical distribution are presented graphically. Mean yearly potential resources of wind on the levels mentioned were calculated according to the method presented in *Wind Atlas for Denmark* [18].

1. INTRODUCTION

The wind, like temperature, air humidity and rainfall, is a basic parameter characterising climate. Usually, climatologists are interested in near-surface measurements made at a standard synoptic station. Meteorologists need information about vertical profiles of the parameters mentioned, and engineers take advantage of the statistical analysis of long sequences of wind speed measurements done in vertical section of low troposphere.

The wind determines the dispersion of air pollutants and is responsible for their transport in the atmosphere. If we construct high emitters (several hundred meters) information about vertical wind and temperature profiles is indispensable. The methods used in such cases are numerous and popular. Nowadays natural environment has been destructed because of the development of conventional energetic industry. Therefore the use of wind as a source of alternative energy seems very attractive. The main advantage of this source is its renewability. In the world, the wind-generated power has been exploited for many years to produce the electric energy, and this energy exploitation continually increases.

The purpose of this paper was to analyse statistically wind speed measurements from 3 radiosonde stations: Legionowo, Łeba and Wrocław. The measurements were done in

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a 5 year period (1991–1995). These are the only such stations in Poland belonging to the Institute of Meteorology and Water Management (IMWM) and doing systematic, standard measurements. Conventionally handling climatologic measurements should concern the data being collected for 10 years or longer, but IMWM made accessible to us in 1996 only 5-year chronological sequences. The data from the next 5 year period we will handled later.

2. WIND CLIMATOLOGY IN POLAND

As yet, in the Polish publications devoted to climatology, especially to wind, we can find the analysis of measurements made at synoptic or climatologic stations. The first monograph of this type was presented by BARTNICKI [1], who especially described the western part of Poland in a 20 year period (1919–1939). GUMIŃSKI [4] supplemented his data by the measurements made in eastern Poland and confirmed the dominance of the west circulation and an impact of topography on the wind structure in Poland. The publications by BARTKOWSKI and WIERZBICKI [2], [3] as well as WIERZBICKI [23] present and discuss wind roses. In *Climate Atlas of Poland* (WISZNIEWSKI [24]), we can find classic wind roses from the periods of 1951–1960 and 1931–1960. In *National Atlas of Poland* [15] apart from wind roses for a ten year period (1951–1960), there were described strong winds and calms. Other important publications of MICHALCZEWSKI [13], KWIECIEŃ [6], KWIATKOWSKI [5], LEWIŃSKA [7], MALICKI, MICHNA [12], MIĘTUS 14], ORLICZ [16], LORENC [9], PARCZEWSKI [17], PLEZLER [19] were devoted to local winds. Vertical variations of wind were examined by analysing pilot or radiosonde measurements, which were, but not necessarily, many year sequences from single stations (BARTKOWSKI, WIERZBICKI [2], MADANY [11], MADANY, SORBJAN [10], PRUCHNICKI, PIWKOWSKI, SORBJAN [20], REICHHART [21]). Longer sequences of radiosonde or pilot measurements were analysed, but not published. Among Polish publications devoted to applied climatology, we have to mention a book of ŻURAŃSKI [25] and an important paper of LORENC [9].

The review of foreign publications devoted to winds cannot be presented within the framework of this article. However, it seems indispensable to pay our attention to *European Wind Atlas* by TROEN and PETERSEN [22]. In this atlas, apart wind roses, the authors calculated potential wind resources for the territory of European Union in regional scale and presented the method of determining such resources in local scale. Poland was not taken into consideration in this atlas.

3. MEASUREMENT CHARACTERISTICS

The measurements from Legionowo, Wrocław and Łeba were made in a 5 year period (1991–1995), twice a day (12 and 00 GMT). We measured wind velocity and direction, atmospheric pressure, geopotential height, air temperature and humidity. The measurements were made to the level of 500 hPa. Additionally we have measured the same parameters at standard synoptic stations. Anemometers, the instruments for measuring and recording the strength and direction of wind, were placed at the following heighst: Legionowo – 15 m, Łeba – 14 m, Wrocław – 12 m. The speed of lower wind was measured by means of cup anemometers M-47 with the accuracy approaching 5%. The wind direction was fixed using metal banner with a slip of 10%.

Unfortunately the, measurement sequences obtained have drawbacks. In the case of Wrocław, we have not data from the period of 1st April–31st December 1992; in the case of Legionowo, from April 1991; in the case of Łeba, from December 1992 and 1st–6th January 1993. Moreover, at all stations some individual measurements are missing. The reconstruction of the missing data is impossible, because the measurement sets are too sparse, rare and not sufficient. The sizes of the sequences processed are presented in table 1.

The wind speed measurements at certain altitudes are not made directly, because sonde must be placed in horizontal plane. The sonde, emitting radio waves, is lifted up by the balloon lighter than the air. Radio or radar is the receiver of signals from sonde. In 1991 all time at each station the RKZ sonde with radar was used. This sonde was also used for the measurements in Legionowo at 12 hours GMT from 1st March 1992 to 30th June1993. The remaining measurements were made by means of the Vaisala sonde at each station. The modern Vaisala sonde uses the Global Position System. In the consequence of disturbances in GPS, some measurements are missing. Establishing the balloon position on the sky lasted about 10 s, and several measurements are done, one after another. Taking the above into account we can state that wind speed at each level is a 4 minute mean value. The accuracy of individual measurement of wind speed reaches on average 0.5 m/s, and wind direction, $\approx 2°$ the directions however are coded every 5°. The error of estimating the height of sonde in lower troposphere is assumed to be 20 hPa.

Geographical co-ordinates ofthe measurement stations can be itemized as follows:

Legionowo, 52°24′N, 20°58′E, 96 m a.s.l.,

Wrocław 51°06′N, 16°53′E, 120 m a.s.l.,

Łeba 54°45′N, 17°32′E, 2 m a.s.l.

The station in Legionowo is situated on the Ciechanowska High Plain, whose height approaches 15 m. This Plain covered with low hills is some distance (about 80 m) from the forest. At a distance of 10 km to the NE we come across Zegrzyński Lake, and at a distance of 1 km to W-WNW residential areas of the town of Legionowo are found. At the station of Legionowo an anemometer 73/M at the height of 15 m above the ground level is installed.

Łeba is a seaside town where in summer a breeze blows. This town is on banks on either side of the Łeba river, on the seasonally flooded terrace of Łebsko Lake. In immediate surroundings of the station there are forests, farm land and some low buildings. At a distance of 1500 m from the station the Łeba town lies.

The radiosonde station in Wrocław is situated outside the city, about 2 km NW from the airport. Anemometer is 12 m above the ground level. In surroundings of the station, the terrain is flat, open, without forests. Single two-storeyed buildings can be found. The city of Wrocław with its differentiated housing lies on the Odra River and its 4 effluents.

4. METHOD OF ANALYSIS

For various reasons the method used in this paper was patterned on *European Wind Atlas* by TROEN and PETERSEN [22]. Therefore, wind on the selected levels (10, 25, 50, 100 and 200 m above the ground) was described statistically and the parameters of the Weibull statistical distribution of its speed were determined in 12 sectors of wind directions.

Because the radiosonde measurements are made when is it possible to determine the next position of the sonde, geopotential heights of measurement points are various in each sonding. Wind speed and direction from measurement levels were interpolated in order to obtain the values assumed as standards. The linear interpolation method was applied in which we made use of two measurement levels nearest to the standard level. Such an interpolation was also made for the levels exceeding the height at which anemometer was put. For each standard level the following generally accepted basic statistical characteristics were calculated: mean yearly frequencies of the wind blowing with a given speed in 12 sectors of wind directions, mean yearly and monthly wind speeds and standard deviations. The sectors of wind directions are defined according to *European Wind Atlas*. Their width is 30°, and 0° direction corresponds to the nord direction (N). The classes of wind speed were similarly defined: their widths equalled 1 m/s except some last classes (compare the tables). The data for 10 m level are obtained due to extrapolation of vertical profiles of the Weibull parameters A and C.

It was stated (PETERSEN et al. [18]) that the sets of wind speed measurements almost always follow the Weibull statistical distribution. *This means that for wind energy purposes, shorter measurement series can be used than are normally required for general wind climatological investigations* (PETERSEN et al. [18]).

When the measured wind speeds V_i are independent then the probability density function for $V_i > 0$ is expressed mathematically by the Weibull distribution:

$$f(V)=\left(\frac{C}{A}\right)\left(\frac{V}{A}\right)^{C-1}\exp\left(-\left(\frac{V}{A}\right)^{C}\right) \quad \text{for} \quad C>0, \quad A>0, \tag{1}$$

where A is the scaling parameter and C denotes the shape parameter.

For the Weibull distribution the statistical quantities can be expressed using the Euler gamma function:

$$\overline{V} = A\Gamma(1+1/C), \tag{2}$$

$$\overline{V}^2 = A^2\Gamma\left(1+2/C\right), \tag{3}$$

$$\sigma_v^2 = A^2\left(\Gamma\left(1+2/C\right) - \Gamma^2\left(1+1/C\right)\right), \tag{4}$$

$$\overline{V}^3 = A^3\Gamma\left(1+3/C\right), \tag{5}$$

where $\Gamma(x)$ is the Euler gamma function.

The parameters A and C are calculated using the maximum probability criterium. For n independent measurements V_i this method is reduced to solving a set of two equations:

$$n/a - \sum V_i^C = 0, \tag{6}$$

$$n/C + \sum \ln V_i - a\sum_i (\ln V_i)V_i^C = 0, \tag{7}$$

where $a = (1/A)^C$.

This set of equations can be solved by means of iteration method. The parameters A and C determined from measurements are presented in figures 1–3 for each standard level and each wind direction sector. Figures 1–3 show that the curves representing these parameters versus height in a half-logarithmic scale are close to straight line at lower heights. This fact allowed determining the values of these parameters on the lowest standard level, which was done by extrapolation of the curves to the 10 m level.

The statistical Weibull distribution can be used to calculate an average potential wind energy

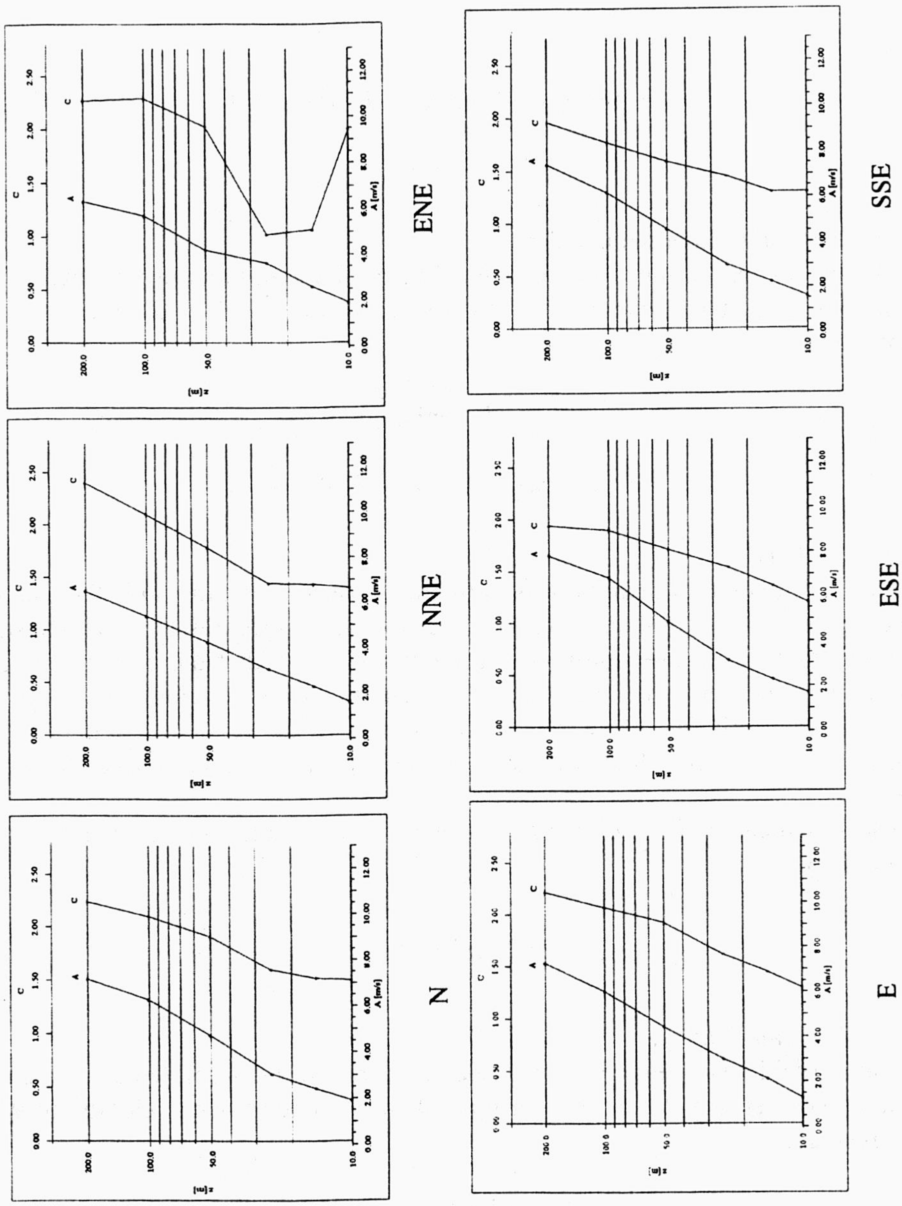
$$\overline{E} = 0.5\rho\int_0^\infty V^3 f\left(V\right)dV, \tag{8}$$

where ρ is an air density.

The available wind energy in each sector on the level determined can be estimated based on mean energy density proportional to mean cube of wind velocity. In W/m^2, it is on average:

$$E_d = 0.5\rho A^3\Gamma(1+3/C). \tag{9}$$

The total potential energy available on each level is calculated as a weighted mean: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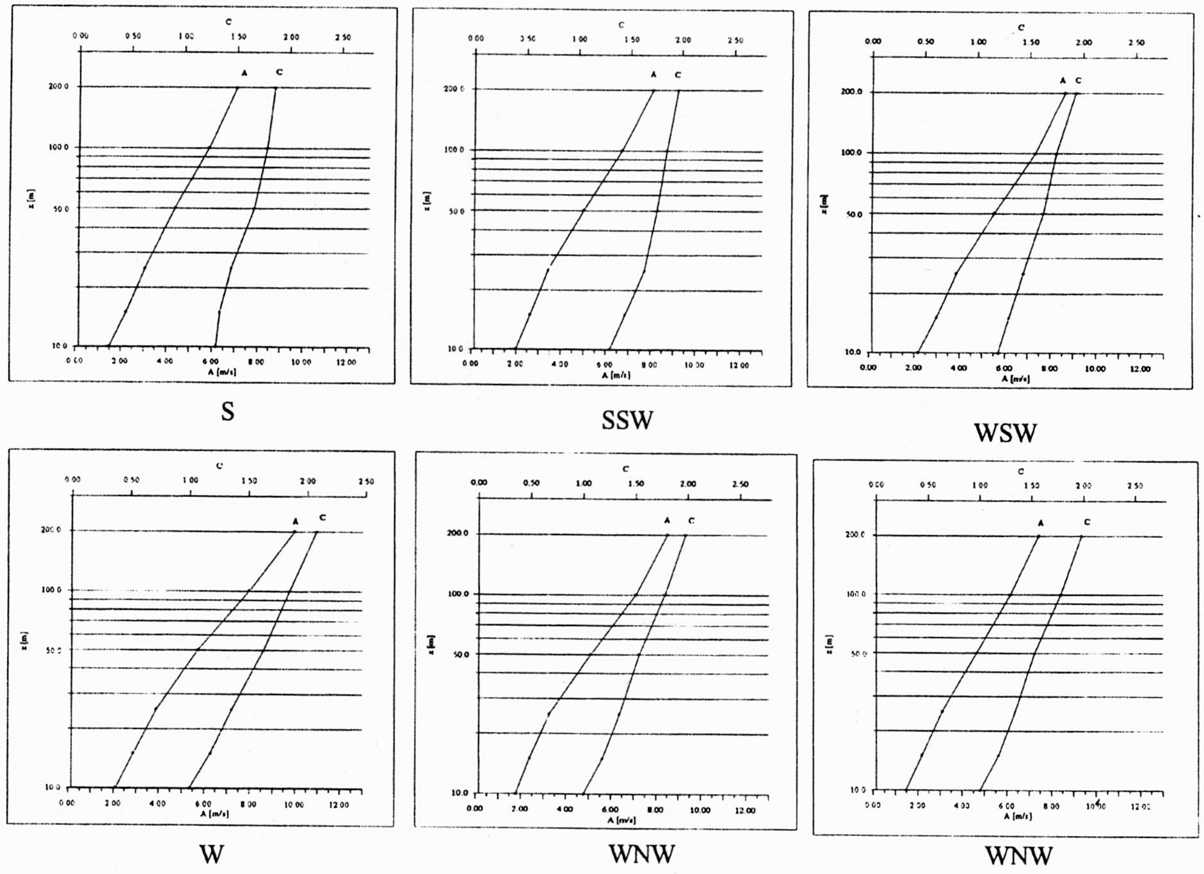
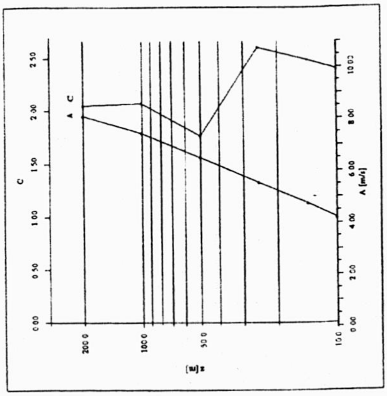


Fig. 1. The Weibull parameters A [m/s] and C for Legionowo station in wind direction sectors as a function of height



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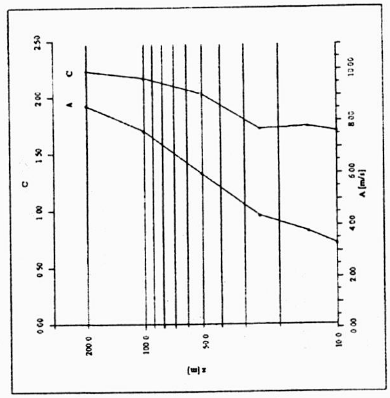

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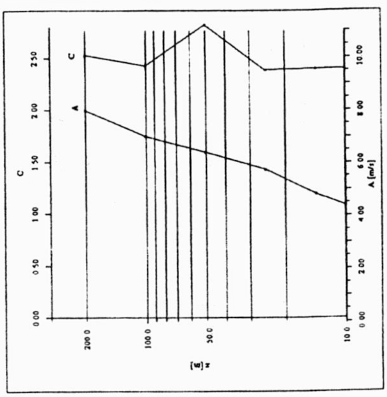

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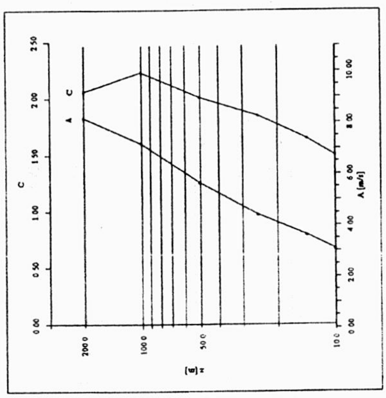

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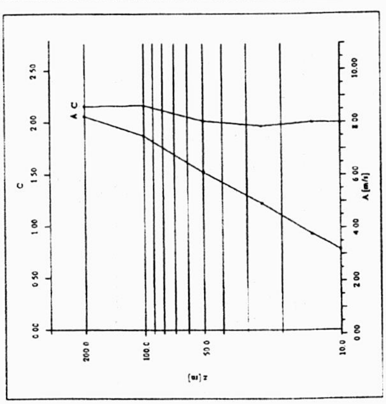

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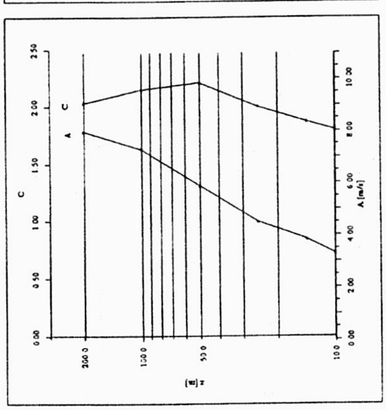

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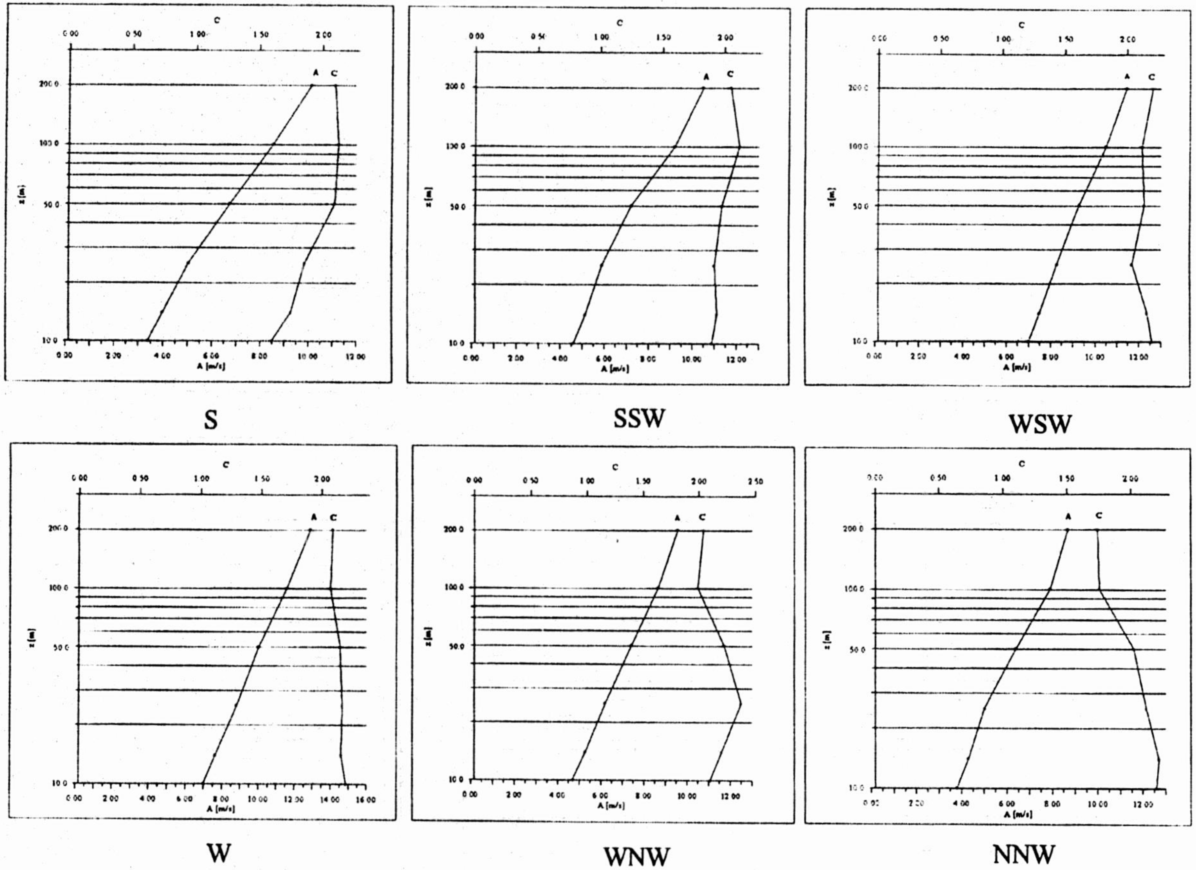
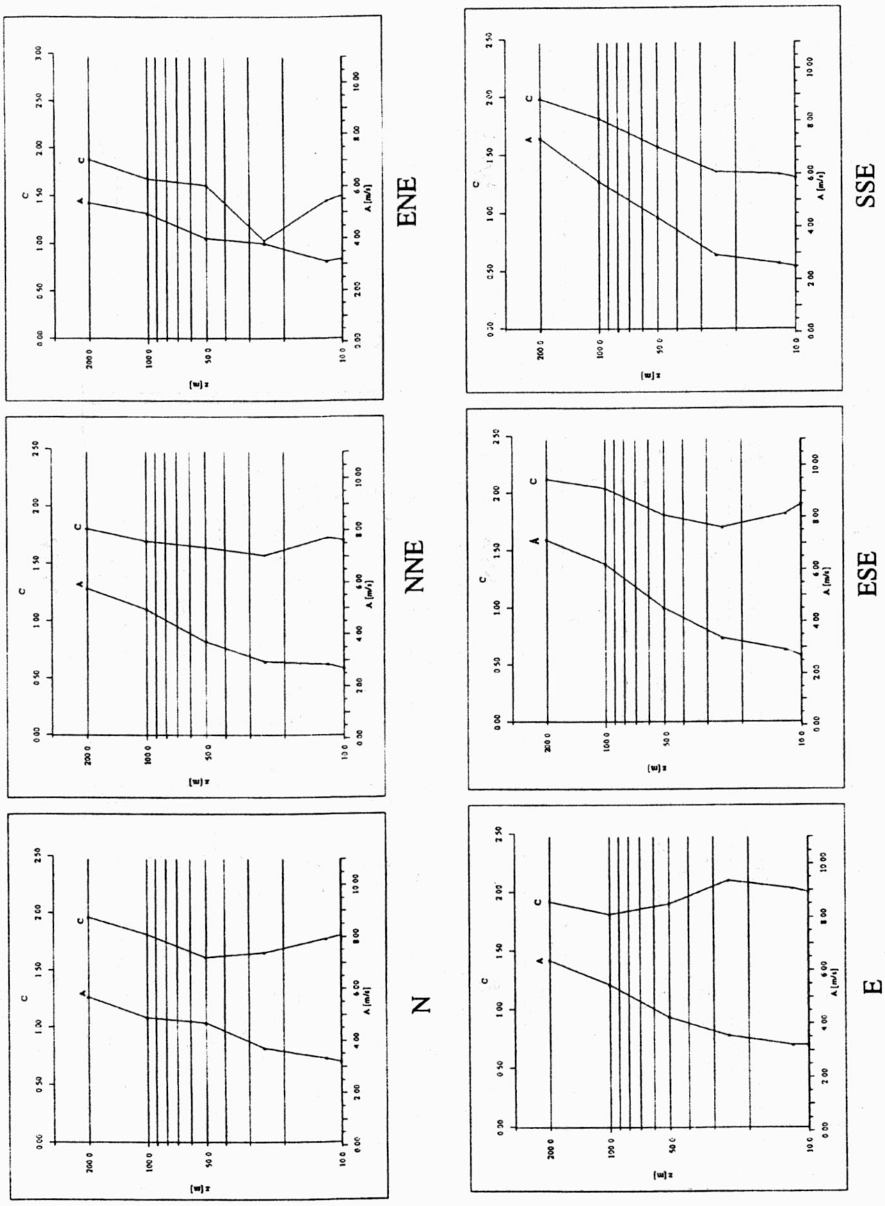


Fig. 2. The Weibull parameters A [m/s] and C for the Łeba station in wind direction sectors as a function of height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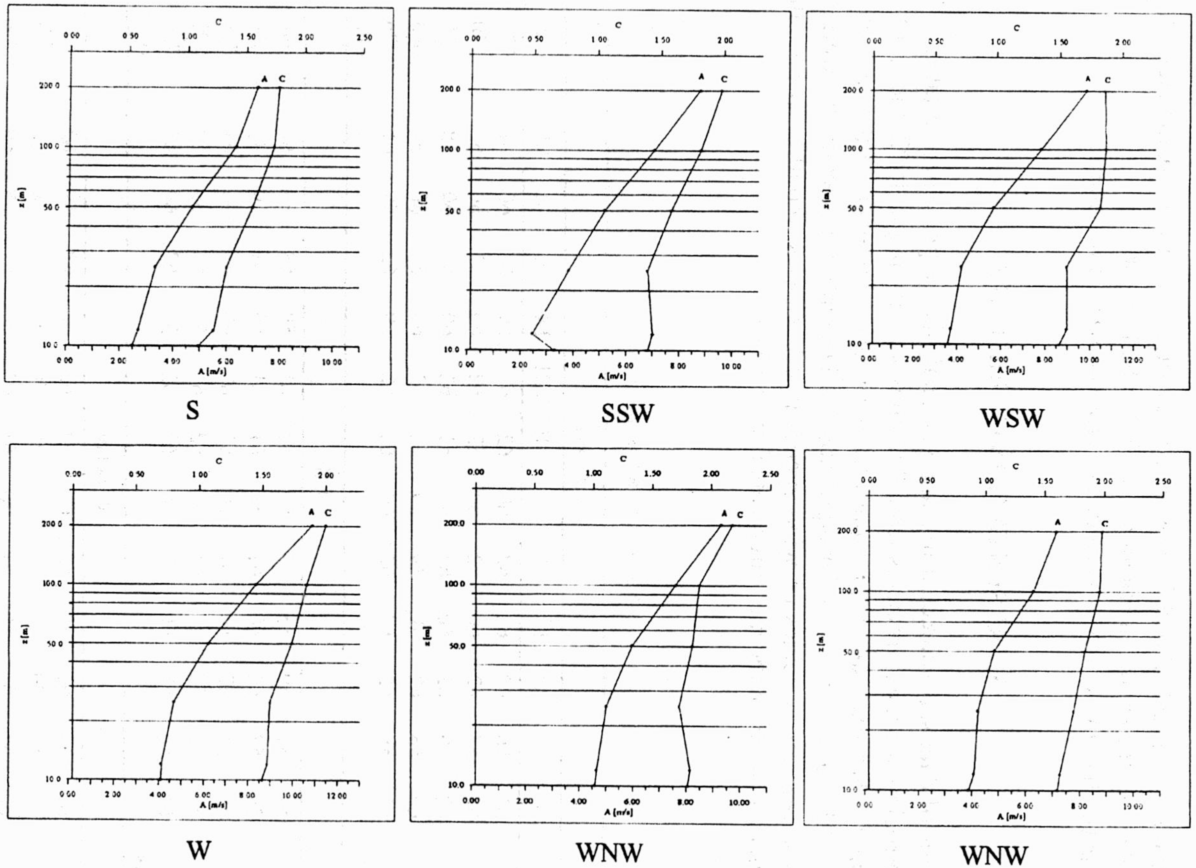


Fig. 3. The Weibull parameters A [m/s] and C for the Wrocław station in wind direction sectors as a function of height

$$E_p = \sum_{i=1}^{12} f_i E_i / \sum_{i=1}^{12} f_i, \tag{10}$$

where E_i is the power calculated for the sector i characterised by the parameters A_i, C_i, and f_i denotes the occurrence frequencies for individual sectors.

In this paper the air density was calculated for standard atmosphere.

5. PRESENTATION OF RESULTS

The sizes of data sets subjected to statistical analysis are presented in table 1. Because in Wrocław the measurements from 9 months are missing in 1992, the results of calculations for Wrocław are mean values from 4 years. Moreover, in the case of Legionowo and Łeba, mean values for April and for December, respectively, were calculated as 4 year mean values of wind speed. In other cases, monthly mean values were calculated based on the measurements from 5 years.

Table 1

Number of radiosonde data

	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	year
Legionowo													
1991	61	56	62	60	62	60	62	62	59	62	60	61	727
1992	61	57	62	60	62	60	62	62	60	62	60	62	730
1993	62	56	62	60	62	60	61	62	60	54	60	58	717
1994	60	56	62	0	59	59	62	62	60	62	60	61	663
1995	61	56	62	60	62	60	62	62	59	62	59	61	726
1991–1995													3563
Łeba													
1991	59	51	59	55	58	54	57	61	59	58	59	60	690
1992	59	58	62	60	61	59	61	61	59	61	59	0	660
1993	46	55	62	60	61	60	61	62	60	61	60	61	709
1994	62	56	60	60	61	60	62	61	59	60	59	62	722
1995	61	56	62	60	62	58	62	62	59	62	60	62	726
1991–1995													3507
Wrocław													
1991	61	55	62	60	62	60	62	62	60	62	59	62	727
1992	57	52	29	0	0	0	0	0	0	0	0	0	138
1993	60	55	61	60	61	50	61	62	60	62	58	60	710
1994	62	56	61	60	61	60	62	62	60	62	60	62	728
1995	62	54	62	60	62	60	62	62	60	62	59	62	727
1991–1995													3030

Table 2 shows monthly variation of mean wind speed. On each level we can see how wind speed increases in winter months. Such a variation did not occur in Legionowo at two lowest levels. Of the stations presented Legionowo in 1991–1995 had the lowest yearly mean wind speed at all levels (with the largest standard deviation). The greatest wind speeds were recorded in Łeba. Because this station is placed near the coast, this can be considered typical.

Table 2

Mean monthly wind speed [m/s] (1991–1995)

Height [m]	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Legionowo												
15	2.8	2.5	2.4	2.3	2.5	2.4	2.2	2.3	2.3	2.2	2.3	2.2
25	3.8	3.3	3.0	2.9	3.2	3.1	2.9	3.0	3.0	2.9	3.1	3.1
50	5.5	4.7	4.3	4.0	4.4	4.2	4.1	4.1	4.3	4.3	4.5	5.0
100	7.8	6.4	5.9	5.4	5.7	5.3	5.2	5.3	5.7	6.0	6.2	7.3
200	9.7	7.9	7.2	6.4	6.6	6.2	5.9	6.0	6.9	7.1	7.5	8.8
Łeba												
14	6.1	5.3	5.3	4.4	4.5	4.8	4.2	4.4	4.3	4.4	4.7	5.2
25	7.3	6.3	6.3	5.2	5.2	5.4	4.9	5.0	5.2	5.3	5.6	6.2
50	8.6	7.6	7.6	6.2	6.0	6.3	5.7	5.9	6.5	6.5	6.7	7.3
100	10.5	9.2	9.0	7.4	6.9	7.3	6.6	6.9	7.7	7.8	8.2	9.0
200	12.1	10.6	10.2	8.1	7.6	7.8	7.2	7.6	8.5	8.7	9.5	10.6
Wrocław												
12	4.0	3.3	3.7	3.2	2.7	2.8	2.8	2.7	3.1	2.8	3.2	3.7
25	4.5	3.6	4.2	3.6	3.2	3.2	3.1	3.0	3.6	3.2	3.5	4.2
50	5.9	4.7	5.3	4.6	4.2	4.2	4.1	3.9	4.3	4.3	4.6	5.5
100	8.0	6.4	6.9	6.0	5.7	5.5	5.1	4.9	5.6	5.7	6.0	7.4
200	10.3	8.0	8.5	7.2	6.7	6.7	6.0	6.1	6.8	7.0	7.3	9.1

In statistical sense, more than 3000-element sets of data (table 1) are large enough, but it is known that the parameters characterising climate vary from year to year. The standard deviation of yearly mean wind speed in a selected 5-year period on the lowest measurement level was not sharp (table 3). The greatest variation was noticed in Legionowo (16%), in Wrocław it approached 7%, and in Łeba about 6%. We show the yearly mean wind speeds and their standard deviations representing a 10 year period (1954–1964) reported from *Meteorological Annals* edited by the Institute of Meteorology and Water Management which can be compared with our data.

Table 3

Mean yearly wind speed (v in m/s) and standard deviation of mean value (σ in m/s) on the anemometer level

Year	1991	1992	1993	1994	1995	1991–1995		1954–1964	
	v	v	v	v	v	v	σ	v	σ
Legionowo	3.7	2.4	2.2	1.8	1.6	2.3	0.37	3.6	0.11
Łeba	5.9	4.6	4.7	4.6	4.3	4.8	0.28	4.5	0.23
Wrocław	2.7	-	2.9	3.3	3.7	3.2	0.22	3.3	0.03

Mean wind speed in Wrocław during 4 years of interest coincides with 11-year mean value from 1954–1964. In principle, this good agreement is also achieved in the case of wind speeds in Łeba. Disconcertingly low is standard deviation from mean year wind speed during this period in Wrocław (0.03 m/s). At this station, the differences between yearly mean wind speeds are at most 2 m/s. Mean wind speeds in Legionowo from a 5-year period are too low, all the more so as the anemometer in Legionowo is installed on the highest level above the ground. In order to explain this fact, we have to study atmospheric circulation in the Middle Europe in this 5-year period. It was impossible within the framework of this paper.

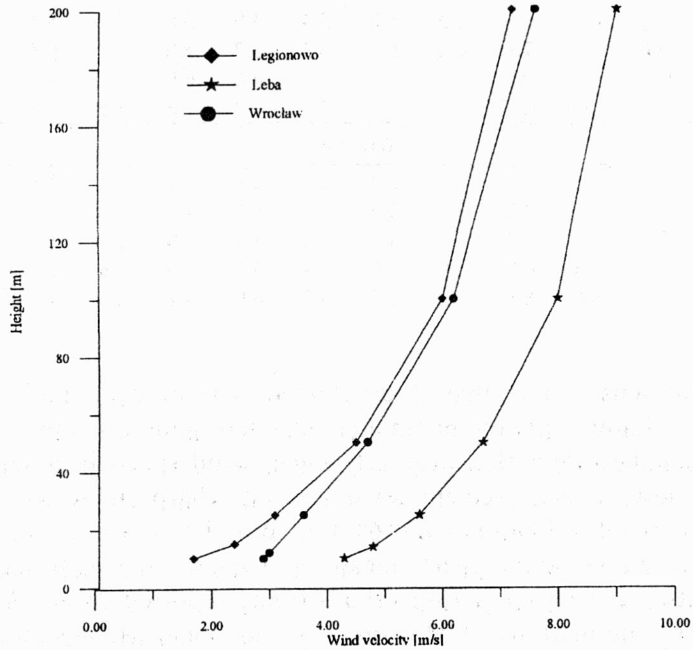


Fig. 4. Mean yearly vertical wind profiles (1991–1995) for Legionowo, Łeba and Wrocław

Table 4

Sectorwise distribution of wind speeds at anemometer height
(f – frequency, per milles; wind speed in m/s)

Legionowo — Number of calms – 35

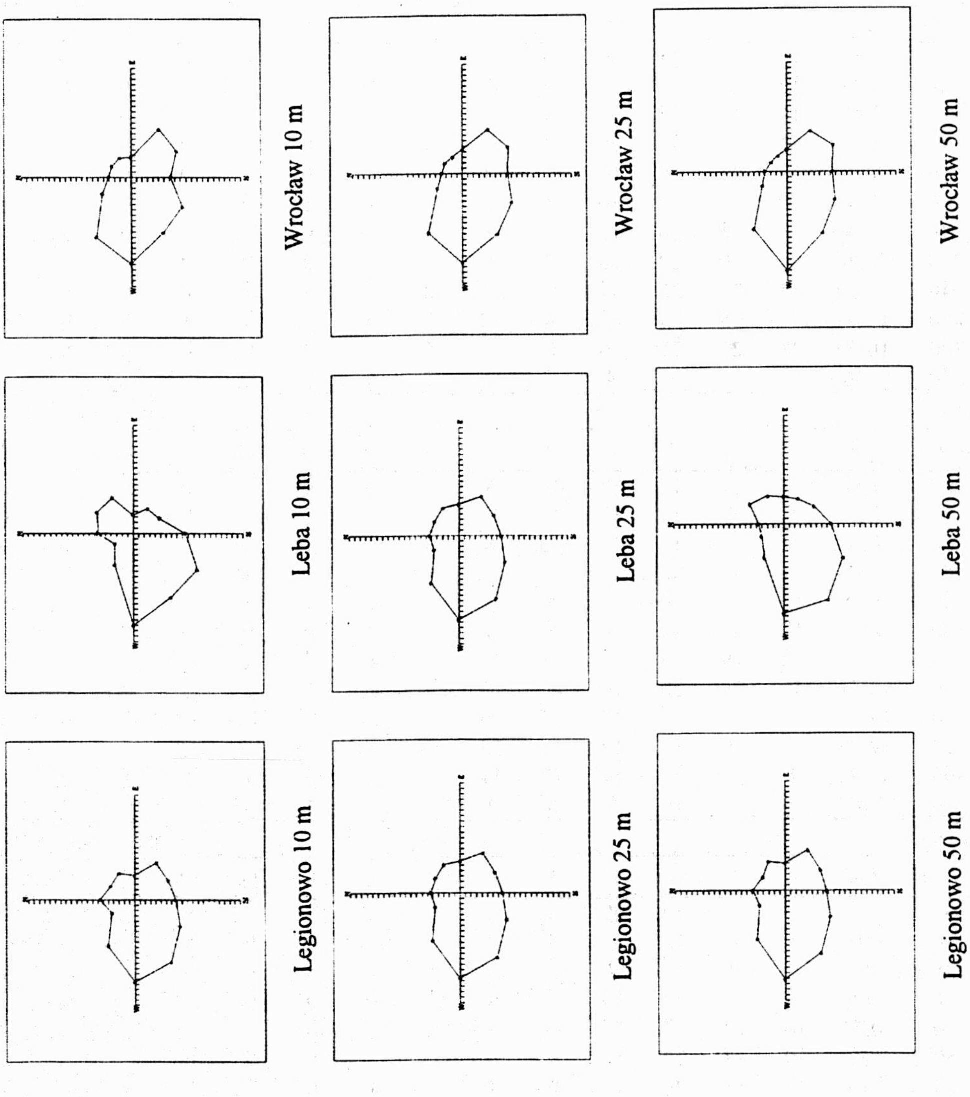
Sector	f [%]	<1	2	3	4	5	6	7	8	9	11	13	15	17	>17
0	6.57	12	18	18	8	6	2	1	1	0	0	0	0	0	0
30	5.24	12	12	14	7	3	3	2	0	0	0	0	0	0	0
60	5.87	14	14	12	9	3	4	1	0	0	0	0	0	0	1
90	4.70	11	13	13	4	2	3	1	0	0	0	0	0	0	0
120	8.19	20	21	18	13	5	3	1	1	0	0	0	0	0	0
150	7.36	20	14	19	10	5	2	2	0	1	0	0	0	0	0
180	7.74	21	15	20	12	5	3	2	0	0	0	0	0	0	0
210	9.96	20	20	20	18	8	6	5	1	0	0	0	0	0	0
240	13.69	28	23	25	23	14	9	6	3	4	1	0	0	0	0
270	15.63	37	35	24	22	8	12	7	5	3	2	1	0	0	0
300	10.09	28	22	21	10	6	5	5	1	2	0	0	0	0	0
330	4.96	17	11	9	4	4	4	1	1	0	0	0	0	0	0

Łeba — Number of calms – 47

Sector	f [%]	<1	2	3	4	5	6	7	8	9	11	13	15	17	>17
0	6.47	7	11	12	13	10	5	3	3	0	0	0	0	0	0
30	7.57	5	6	10	13	11	11	9	7	2	0	0	0	0	0
60	7.54	3	7	12	12	15	8	10	6	1	0	0	0	0	0
90	3.35	4	6	6	6	5	3	2	1	1	1	0	0	0	0
120	5.23	10	12	5	7	8	5	2	2	1	1	0	0	0	0
150	5.55	10	8	10	9	8	4	3	4	0	0	0	0	0	0
180	9.51	12	19	14	13	11	10	6	6	3	1	0	0	0	0
210	13.41	8	16	20	15	20	17	14	12	5	7	1	0	0	0
240	13.67	3	6	8	13	13	16	18	17	14	13	10	6	0	0
270	17.08	2	7	10	14	19	25	18	28	10	18	12	6	2	1
300	6.78	2	3	9	14	12	11	4	6	3	1	1	1	0	0
330	3.85	2	4	10	6	8	4	2	1	1	0	0	0	0	0

Wrocław — Number of calms – 220

Sector	f [%]	1	2	3	4	5	6	7	8	9	11	13	15	17	>17
0	4.13	4	7	12	8	5	2	3	0	0	0	0	0	0	0
30	4.02	2	9	16	6	4	2	1	0	0	0	0	0	0	0
60	4.09	2	9	13	9	5	1	1	0	0	0	0	1	0	0
90	3.66	3	6	9	10	6	3	1	0	0	0	0	0	0	0
120	10.21	10	15	32	27	11	6	0	1	0	0	0	0	0	0
150	9.57	19	18	27	12	9	6	4	1	0	0	0	0	0	0
180	7.19	15	13	20	10	6	3	2	1	0	1	0	0	0	0
210	10.85	15	14	24	17	15	7	10	5	2	0	0	0	0	0
240	11.71	12	15	24	21	17	12	11	3	2	1	1	0	0	0
270	15.84	10	19	32	32	21	16	10	7	4	5	1	0	1	0
300	12.67	4	12	26	22	21	15	9	7	6	5	0	0	0	0
330	6.06	2	7	16	8	10	7	5	2	2	0	0	1	0	0


Wrocław 10 m
Wrocław 25 m
Wrocław 50 m
Leba 10 m
Leba 25 m
Leba 50 m
Legionowo 10 m
Legionowo 25 m
Legionowo 50 m

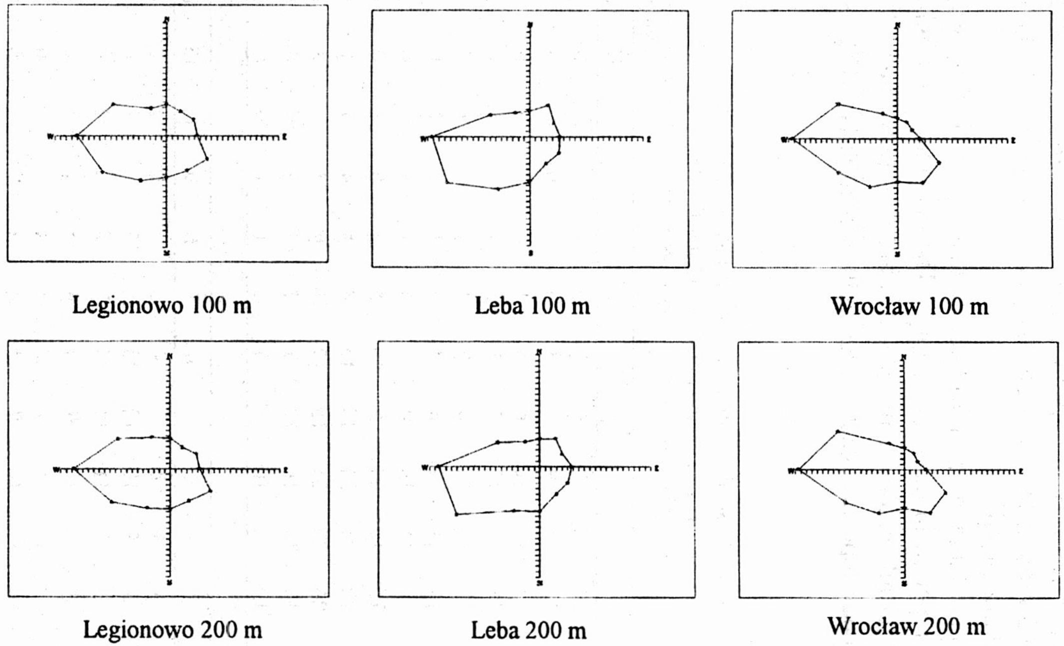


Fig. 5. Wind roses for Legionowo, Łeba and Wrocław on 5 standard levels (1 unit means 1%)

The yearly mean wind speeds at all stations increase systematically with height (figure 4). Vertical wind profiles for Legionowo and for Wrocław lie near each other. The curve $V(z)$ for Łeba lies, independently of the level, to the right side of other curves in a distance of about 2 m/s. In figure 4, there are also presented the wind speeds for the level of 10 m. Bottom parts of the curves prove that within the layer of ca 100 m above the ground level the changes in wind speed with height are represented by a logarithmic profile.

Wind roses (figure 5 and tables 4–8) indicate that the winds from west sectors prevailed, which was reported in numerous papers. The maximum of wind frequency fell on the sector 270° for all stations, especially this in Łeba. Low value of the secondary maximum of frequency appears at each station in the direction 120° (figure 5).

Table 5

Sectorwise distribution of wind speeds on 25 m level
(f – frequency, per milles; wind speed in m/s)

Legionowo															Number of calms – 6
Sector	f[%]	<1	2	3	4	5	6	7	8	9	11	13	15	17	>17
0	5.40	6	13	15	7	6	2	2	1	1	0	0	0	0	0
30	5.17	7	12	13	9	4	3	3	1	0	0	0	0	0	0
60	5.88	6	15	12	10	6	6	1	0	1	0	0	0	0	1
90	5.74	6	15	14	12	5	1	3	1	0	1	0	0	0	0
120	8.29	13	17	18	15	9	6	3	1	1	1	0	0	0	0
150	7.39	13	15	15	17	6	2	3	1	1	1	0	0	0	0
180	7.76	14	14	15	15	9	5	4	1	1	0	0	0	0	0
210	9.81	13	15	19	23	9	10	5	3	0	1	0	0	0	0
240	13.61	18	20	21	24	18	15	8	5	4	3	1	0	0	0
270	15.60	22	26	27	23	15	17	10	6	4	3	2	0	1	0
300	10.09	20	16	18	16	12	7	7	2	2	1	0	0	0	0
330	5.26	9	10	10	10	5	5	2	1	1	0	0	0	0	0
Łeba															Number of calms – 2
Sector	f[%]	<1	2	3	4	5	6	7	8	9	11	13	15	17	>17
0	4.02	1	3	6	8	9	5	3	3	2	1	0	0	0	0
30	7.30	2	3	5	10	15	15	10	7	6	1	0	1	0	0
60	7.28	1	3	7	11	17	14	7	8	3	2	0	0	0	0
90	5.48	3	4	10	10	9	9	4	4	1	1	0	0	0	0
120	5.05	3	7	10	5	7	9	3	3	1	1	0	0	0	0
150	5.93	3	10	11	10	7	7	4	4	2	2	0	0	0	0
180	8.76	3	12	11	12	14	12	8	6	7	3	1	0	0	0
210	13.84	4	8	23	15	16	20	17	11	9	10	5	0	0	0
240	14.81	2	4	10	9	15	18	17	15	15	19	10	9	4	2
270	16.69	2	2	9	10	13	19	21	18	17	23	15	7	7	4
300	6.90	1	2	4	10	14	11	11	7	3	4	1	1	0	0
330	3.94	0	2	8	9	7	5	4	2	1	1	0	0	0	0

Wrocław														Number of calms – 20
Sector	*f* [%]	<1	2	3	4	5	6	7	8	9	11	13	15	17	>17
0	3.82	3	6	9	7	3	5	3	1	1	0	0	0	0	0
30	3.69	4	7	12	6	4	2	1	1	0	0	0	0	0	0
60	3.55	4	7	8	8	3	2	1	0	0	0	0	0	0	1
90	4.38	2	8	9	11	6	7	0	0	0	0	0	0	0	0
120	9.30	12	10	24	23	14	7	1	2	1	0	0	0	0	0
150	9.67	20	16	27	12	8	6	6	1	1	0	0	0	0	0
180	8.30	15	14	15	15	9	4	4	3	2	1	0	0	0	0
210	10.43	17	15	17	15	13	8	9	4	3	2	0	0	0	0
240	12.79	14	15	21	21	17	17	9	6	3	4	1	0	0	0
270	16.32	14	15	26	33	22	17	11	8	9	6	3	0	1	0
300	12.43	6	12	21	20	19	16	7	9	6	6	2	1	0	0
330	5.32	3	6	12	10	6	5	6	3	1	1	0	0	0	0

Table 6

Sectorwise distribution of wind speeds on 50 m level (*f* – frequency, per milles; wind speed in m/s)

Legionowo														Number of calms – 6
Sector	*f* [%]	<1	2	3	4	5	6	7	8	9	11	13	15	17	>17
0	5.96	3	6	9	10	11	8	5	3	3	1	0	0	0	0
30	4.75	3	6	9	9	5	5	5	2	1	0	1	0	0	0
60	6.04	2	8	10	12	9	10	4	2	1	1	0	0	0	0
90	4.98	3	4	9	12	6	7	3	3	2	0	0	0	0	0
120	8.46	6	10	10	16	12	12	8	3	3	4	1	1	0	0
150	7.49	6	11	12	11	11	8	6	4	2	2	1	0	0	0
180	7.59	8	10	11	13	10	9	8	5	1	2	1	0	0	0
210	9.64	6	11	11	15	16	12	8	7	5	4	1	1	0	0
240	13.22	10	10	14	18	16	17	14	10	10	9	1	1	0	1
270	16.19	8	17	19	21	20	24	13	14	6	10	7	1	1	1
300	10.26	9	12	14	14	11	10	11	8	7	3	2	1	0	0
330	5.42	5	6	7	9	8	8	3	4	3	1	0	0	0	0

Łeba														Number of calms – 2
Sector	*f* [%]	<1	2	3	4	5	6	7	8	9	11	13	15	17	>17
0	4.65	1	4	5	5	6	9	5	6	1	4	1	1	0	0
30	7.16	2	1	4	8	11	11	12	9	8	4	0	0	0	0
60	5.88	1	3	4	7	10	10	7	7	3	5	1	0	0	1
90	4.96	2	2	6	5	6	7	9	5	3	3	0	0	0	0
120	5.25	1	6	5	7	7	9	5	6	3	3	1	0	0	0
150	6.39	2	5	8	9	7	7	9	7	6	4	1	0	0	0
180	8.62	2	7	7	11	7	10	11	9	9	12	3	1	0	0
210	12.52	1	9	14	11	9	17	14	11	10	17	9	3	1	0
240	16.18	2	3	6	8	12	19	20	14	19	24	12	12	9	3
270	16.52	1	4	6	9	10	14	18	15	15	30	19	10	7	9
300	7.16	1	3	3	9	9	11	8	9	7	7	4	2	1	0
330	4.71	1	2	5	9	4	6	7	5	2	4	1	1	0	0

Wrocław													Number of calms – 3		
Sector	*f* [%]	<1	2	3	4	5	6	7	8	9	11	13	15	17	>17
0	4.06	3	5	5	9	4	4	4	2	2	2	0	0	0	0
30	3.30	3	5	10	3	4	3	2	2	0	0	0	0	0	0
60	3.27	2	6	6	5	4	3	3	1	1	1	0	0	0	0
90	4.00	3	4	8	9	6	5	2	3	1	0	0	0	0	0
120	8.62	7	8	11	18	17	14	4	3	2	2	1	0	0	0
150	9.84	9	13	19	15	13	11	7	5	5	3	1	0	0	0
180	8.37	8	8	15	13	8	10	8	6	3	4	1	0	0	0
210	10.18	5	16	14	11	11	13	11	5	6	6	3	1	0	0
240	12.98	5	13	13	15	20	21	17	9	8	7	4	1	0	0
270	18.10	8	9	19	28	25	20	19	15	11	13	9	3	1	1
300	12.09	3	11	12	17	15	21	11	9	10	8	3	1	1	0
330	5.19	2	5	9	11	7	6	4	4	1	3	0	0	0	0

Table 7

Sectorwise distribution of wind speeds on 100 m level (*f* – frequency, per milles; wind speed in m/s)

Legionowo													Number of calms – 4		
Sector	*f* [%]	<1	2	3	4	5	6	7	8	9	11	13	15	17	>17
0	5.56	2	2	5	7	8	9	8	5	5	4	1	1	0	0
30	4.92	1	6	6	5	7	8	7	5	2	1	0	0	0	0
60	5.59	1	3	6	8	8	9	8	5	3	3	1	0	0	0
90	5.42	3	2	5	7	6	12	8	3	3	3	1	1	0	0
120	8.37	3	6	8	6	11	11	10	9	5	10	4	1	1	1
150	7.30	1	7	9	9	8	10	8	7	5	4	3	1	1	1
180	7.53	3	7	8	8	8	12	9	7	3	4	3	1	0	0
210	9.33	2	8	8	10	11	14	10	8	6	10	5	2	1	0
240	13.26	4	9	9	12	14	19	15	11	8	16	8	4	3	2
270	16.08	4	6	11	17	15	18	16	15	11	22	12	6	3	4
300	11.05	3	7	9	13	12	15	10	10	9	11	6	5	1	1
330	5.59	2	3	4	8	7	12	6	5	4	5	0	1	1	0

Łeba													Number of calms – 2		
Sector	*f* [%]	<1	2	3	4	5	6	7	8	9	11	13	15	17	>17
0	4.65	1	2	3	4	5	4	9	5	3	6	3	1	0	1
30	6.65	0	4	4	4	10	9	11	6	5	7	3	1	0	0
60	4.96	0	2	3	5	6	9	6	5	2	6	3	2	0	1
90	5.36	1	3	3	5	7	5	5	7	5	7	3	1	0	0
120	5.94	0	2	6	5	7	8	7	9	6	6	2	1	0	1
150	5.71	1	2	4	4	7	8	5	7	6	7	5	1	0	0
180	8.36	1	4	5	6	7	9	8	5	9	14	9	3	2	1
210	11.19	1	5	7	6	5	12	13	11	8	15	16	9	2	3
240	16.89	0	4	7	6	8	14	19	11	16	31	15	15	11	10
270	17.29	1	2	4	7	10	12	14	16	13	27	24	15	9	19
300	7.94	1	4	3	9	4	7	9	9	7	14	6	4	1	2
330	5.06	1	2	4	7	5	7	4	4	5	6	3	3	1	1

Wrocław												Number of calms – 2			
Sector	f[%]	<1	2	3	4	5	6	7	8	9	11	13	15	17	>17
0	3.63	1	4	7	5	5	4	4	1	2	1	1	0	0	0
30	3.40	1	5	5	5	4	5	3	3	1	1	1	0	0	0
60	3.07	1	5	6	2	4	3	3	2	2	2	0	0	0	0
90	4.10	2	3	5	6	7	5	4	2	5	1	1	0	0	0
120	8.82	4	4	6	12	11	16	13	8	4	8	1	1	0	0
150	9.35	5	7	12	11	14	13	10	8	5	6	3	1	0	0
180	7.93	3	5	12	7	9	9	11	6	5	7	3	2	0	0
210	10.14	2	7	12	9	9	12	11	10	9	10	6	4	2	0
240	12.45	3	4	10	14	9	13	15	10	12	17	8	5	4	1
270	19.38	6	7	12	15	20	20	19	19	15	27	15	10	6	5
300	12.52	2	7	9	10	14	17	15	11	12	14	8	3	2	2
330	5.21	2	3	5	9	7	7	5	5	2	6	1	1	0	0

Table 8

Sectorwise distribution of wind speeds on 200 m level (f – frequency, per milles; wind speed in m/s)

Legionowo												Number of calms – 2			
Sector	f[%]	<1	2	3	4	5	6	7	8	9	11	13	15	17	>17
0	5.59	1	1	3	6	6	7	9	6	6	6	3	1	0	0
30	4.52	0	2	5	4	5	7	8	6	3	4	1	0	0	0
60	5.50	1	3	3	8	5	8	8	6	4	4	1	0	0	0
90	5.34	1	3	4	3	4	10	8	5	7	4	3	1	0	0
120	8.45	1	4	8	4	10	12	8	5	8	12	8	4	0	1
150	6.91	1	3	6	7	7	10	9	5	7	7	4	2	1	1
180	7.50	1	5	9	7	8	10	6	6	6	8	4	3	1	0
210	8.45	1	4	6	6	8	13	8	7	5	10	6	6	3	1
240	12.41	2	3	10	7	9	16	13	13	8	19	9	5	6	4
270	17.66	2	4	5	10	12	18	17	17	21	24	15	14	9	11
300	11.01	1	4	8	8	11	13	9	8	10	14	10	8	3	1
330	6.66	0	3	3	6	7	13	7	9	5	7	3	2	1	1

Łeba												Number of calms – 2			
Sector	f[%]	<1	2	3	4	5	6	7	8	9	11	13	15	17	>17
0	4.99	0	2	4	2	5	7	4	6	5	6	5	1	1	1
30	5.76	0	1	2	6	6	6	5	7	7	8	5	2	0	0
60	4.62	0	1	3	5	6	3	7	7	2	5	3	3	1	1
90	5.71	0	2	5	5	6	8	6	5	4	10	3	3	1	1
120	5.82	1	3	3	5	4	9	7	5	5	11	3	2	0	1
150	5.88	1	1	4	5	5	6	3	8	4	9	6	4	1	0
180	8.16	0	2	4	6	5	6	7	6	7	12	9	9	6	3
210	9.33	0	3	4	5	5	9	8	8	10	9	11	9	7	6
240	17.46	0	3	4	7	9	8	17	14	14	30	23	17	14	14
270	18.40	0	1	3	6	9	12	12	15	13	30	21	18	15	29
300	8.73	1	2	3	7	7	9	9	9	8	13	9	7	2	4
330	5.14	0	3	5	4	3	6	6	5	4	6	4	4	1	2

Wrocław														Number of calms – 0
Sector	f [%]	<1	2	3	4	5	6	7	8	9	11	13	15	17	>17
0	3.99	1	4	5	5	5	7	6	3	2	1	1	0	0	0
30	3.40	2	2	4	5	5	4	3	3	3	2	1	0	0	0
60	2.77	1	3	5	2	4	4	3	1	2	1	0	0	0	0
90	3.93	2	4	2	4	6	4	5	4	4	4	1	1	0	0
120	8.65	1	3	5	9	12	14	10	8	6	9	5	2	0	1
150	9.34	2	5	7	7	11	12	11	9	7	13	7	2	0	0
180	7.16	1	5	8	8	6	8	8	6	4	7	6	4	1	0
210	9.37	2	4	5	5	7	11	9	9	7	14	9	7	3	2
240	12.41	2	3	7	8	12	12	8	9	8	18	12	9	8	9
270	19.48	2	6	5	10	15	16	13	14	15	28	19	21	15	17
300	13.99	2	2	7	7	11	14	14	14	14	21	17	10	4	4
330	5.51	1	3	5	6	6	7	6	5	3	7	4	1	0	0

In Wrocław, a large number of atmospheric calms (220) on the anemometer level is worthy of notice. In Legionowo, as well as in Łeba the calm occurs 5–6 times rarer. On higher levels at each station, west winds prevail, but their per cent in sector 270° increases with height and the share of strong winds is larger and larger. From 50 m above a ground level the winds blowing with a speed grater than 17 m/s are frequent.

The Weibull parameters A and C versus height for each wind direction sector are presented in figure 1 (Legionowo), figure 2 (Łeba) and figure 3 (Wrocław). The Weibull parameters A and C for a chosen height (vertical scale) can be read on the bottom and top horizontal scales, respectively. The curves $A(z)$, $C(z)$ are used for calculations (eqs. (9) and (10)) of a potential wind energy (table 9). This potential energy is equal to the mean wind power calculated for 1 m^2 of the surface perpendicular to air flow. The values calculated for Łeba are approximately equal to the sum of potential energies at two remaining stations. This result is in agreement with the results reported in *European Wind Atlas* [22] (p. 37, figure 23) for the level of 50 m if we assume the roughness type for Łeba as "at a sea coast", and "open plain" for Wrocław and Legionowo. It should be stressed that really useful wind energy is determined using power characteristics of wind turbine, so the electric energy produced by the turbine is lower than a potential wind energy.

Table 9

Mean yearly potential energy of wind [W/m^2]

Height [m]	10	25	50	100	200
Legionowo	16	60	132	285	453
Łeba	116	239	383	627	890
Wrocław	53	81	147	314	565

6. SUMMARY

European Wind Atlas, whose luxury edition appeared in 1989, did not provide any information about Polish territory. Because of the lack of Polish climatologic papers dealing with vertical wind profile, the authors decide to fill partially this gap. The results of measurements made at three Polish aerological stations were collected and examined. Unfortunately, we have got access only to 5-year sets of measurements collected by the Institute of Meteorology and Water Management in Legionowo, Łeba and Wrocław.

Because of many reasons our investigations were patterned on *European Wind Atlas*, hence winds on the standard levels (10, 25, 50, 100 and 200 m above ground) were statistically described and the parameters of statistical distribution were calculated in 12 wind direction sectors. It was stated (PETERSEN et al. [18]) that nearly all sets of measured wind speeds could be arranged according to statistical Weibull distribution, which allowed us to analyse the data sets shorter than those used in climatologic studies. For each standard level and each direction sector, the parameters A and C of the mentioned distribution were calculated (figures 1, 2, 3). This enabled calculation of mean potential wind energy for Legionowo, Łeba and Wrocław. The vertical profiles of wind speeds at those stations were also shown (figure 4). In the nearest future, those investingations will be continued.

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ANALIZA STATYSTYCZNA RADIOSONDAŻOWYCH POMIARÓW PRĘDKOŚCI WIATRU NA OBSZARZE POLSKI

Korzystając z metody opisanej w *European Wind Atlas* [18], przeanalizowano pomiary radiosondażowe z okresu 1991–1995 wykonane w trzech stacjach: Legionowo, Łeba i Wrocław. Dane te udostępnił IMGW w celach naukowych. Na 5-ciu poziomach (do 200 m) obliczono rozkłady częstości składowych wektora wiatru oraz parametry A i C rozkładu statystycznego Weibulla. Wiele wyników przedstawiono graficznie. Posługując się metodą podaną przez PETERSENA et al. [18], na 5-ciu poziomach obliczono średnią roczną energię potencjalną wiatru w wymienionych stacjach.