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Variability of geostrophic airflow over Poland, 1951-2014

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Abstract. The paper presents the analysis of the anemological conditions variability over Poland with the usage of geostrophic wind vector as an objective (and homogenous) information concerning the airflow over the area of research. The geostrophic wind vector components are calculated using SLP and air temperature (at sigma 995 level) at selected gridpoints which were subsequently interpolated to a central point thus describing the average flow over the research area. The data originated from NCEP/NCAR Reanalysis and its temporal range was 1951-2014. The analysis covers statistical characteristics of the overall annual cycle as well as trend analysis of the airflow features over Poland: geostrophic wind vector module (V), and its zonal (u) and meridional (v) components. Aside from general statistical characteristics for averages and extremes (quantiles 10% and 90%) GEV distribution was fitted to maximum annual/monthly geostrophic wind speed values which allowed the estimation of return levels for selected return periods. For the period 1951-2014 average geostrophic wind velocity over Poland equals 7.4 ms^{-1} and the 99% quantile exceeds 21 ms^{-1}. Maximum speed ever recorded equalled 37.6 ms^{-1}. Geostrophic wind vector module (V) and its components (u, v) exhibit clear annual cycle with the highest V values in winter. Positive (westerly) u values dominate in the colder part of the year. In spring the dominance of eastern advection appears and in summer the prevalence of westerly flow is only minimal. There exists a distinctive variability of decadal directional structure and this is clearly visible in the substantial increase in the share of western sector frequencies in 1981-1990 and following decade. Monthly V averages do not exhibit (except October) statistically significant trends whereas in spring and summer months as well as for annual averages of u component trend is significant. There are virtually no significant changes in the v values. GEV analysis allowed the year to be divided into two parts. Warm one with relatively low return levels – for many months not exceeding 20 ms^{-1} even for 50y return period. On the other hand winter months return level values exceed 30 ms^{-1} even for relatively short return periods (20y) with upper estimates for 100y return period closing to 40 ms^{-1}.

Key words:
geostrophic wind,
Poland,
anemological conditions variability

Introduction

One of the ways to analyze the multiannual anemological conditions is the utilization of synthetic circulation indices basing on other meteorological variables. This is especially important in case of the situation when the homogeneity of the data is doubtful which in the case of the long term wind measurements is very often true which was stressed in the WASA (Waves and Storm in the North Atlantic) project findings (Carretero et al. 1998). The problems with homogeneity may be caused by equipment changes, station relocation or changes in the environment surrounding the station. This poses a serious impediment when analyzing the multiannual series and deriving proper estimates of statistical characteristics.

Sea level pressure (SLP) field may serve as a variable utilizable in the analysis of an air flow. The index that can be used in this case is a geostrophic wind vector (Carretero et al. 1998). Its module and components as well as the resulting wind direction provide detailed information on the air flow at selected location. This method was extensively used in the climate research providing valuable information on the airflow characteristic and was also utilised in downscaling procedures (e.g. Thorndike 1982; Miętus 1993, 1994, 1995, 1996; Marosz 1999; Kimura and Wakatsushi 2000). Earlier analysis of geostrophic wind vector characteristics for Poland (Marosz and Miętus 2012) utilised in situ measurements from 14 stations and aimed at regionalisation of Poland basing on geostrophic wind vector characteristics. In present research the reanalysis data with confirmed homogeneity, and higher temporal resolution were used. Also, Degirmendžić et al. (2004) analysed the geostrophic wind vector component characteristics over Central Europe and linked it with the air temperature and precipitation totals variability in Poland.

The aim of the research was to investigate the multiannual (1951-2014) anemological conditions variability over Poland with the application of geostrophic wind vector as an objective (and homogenous) information describing the airflow over the area of research (Fig. 1). The scope of the analytical methods comprised monthly and annual statistical characteristics of geostrophic wind vector components (u - zonal, v – meridional), velocity (V) and wind direction stability coefficient (η) together with the analysis of wind directional structure. Also, 64-year trend analysis of annual and monthly geostrophic wind vector characteristics was performed together with the fitting of GEV (Generalized Extreme Value) distribution (Coles 2001) to annual and monthly maxima of wind speed (V_{max}). This provided further insight into the possibility of occurrence of wind speed at disastrous levels.

Data and methods

The data originated from NCEP/NCAR Reanalysis (Kalnay et al. 1996) and comprised: Sea level pressure (SLP) and air temperature at sigma 995 level (t_{995}) fields covering the period 1951-2014 (with 6h temporal resolution). The spatial extent covered Central Europe (10.0°E-27.5°E, 47.5°N-57.5°N) and individual grid point SLP and t_{995} values have been used to calculate geostrophic wind vector components (Fig. 1) which were subsequently bi-lineary interpolated (Kreysig 1972) to a central point (17.75°E, 52.08°N – marked with a diamond in Fig. 1) providing the data necessary to characterize generalised air flow conditions over Poland.

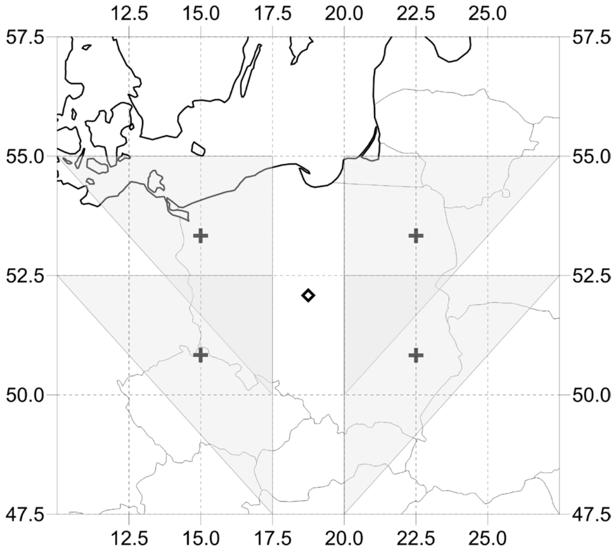

Fig. 1. Location of triangles (shaded areas) used to calculate the geostrophic wind characteristics (crosshairs marking the central points). A diamond indicates a central point for which an analysis of geostrophic wind is performed

Geostrophic wind is a theoretical air movement in the so called free atmosphere (without friction force taken into account). Its speed (V) can be calculated with the following equation:

$$V = \frac{1}{2\Omega\rho\sin\varphi}\frac{dp}{dl}$$

where:
V – geostrophic wind speed (ms^{-1}),
Ω – Earth's angular velocity – $7{,}2921 \cdot 10^{-5} s^{-1}$,
ρ – air density,
φ – latitude,
dp/dl – horizontal SLP gradient.

This allows a relatively straightforward calculation of the geostrophic wind velocity (V) providing the prior knowledge of horizontal SLP gradient (dp/dl) and air density (ρ) (calculated on the basis of air temperature and pressure). Nearly every textbook on meteorology provides detailed description of the geostrophic flow theoretical foundations and some practicalities concerning the calculations of the geostrophic wind speed and its components are also presented by Miętus (1996) and Marosz and Miętus (2012). For the sake of brevity only the basics of the applied approach are covered herein.

The calculations base on solving of the set of equations where the values of SLP are mathematically related with the coordinates of the vertices of the triangle comprising the area of interest. The vertices' coordinates are given in kilometres in Cartesian framework (orthographic projection) with the central point located at the tangential point of the projection plane. This point is, at the same time, the origin of the geostrophic wind vector. The equation is as follows:

$$\begin{cases} SLP_1 = ax_1 + by_1 + c \\ SLP_2 = ax_2 + by_2 + c \\ SLP_3 = ax_3 + by_3 + c \end{cases}$$

where:
SLP – sea level pressure,
x, y – triangle vertices coordinates,
a, b, c – equation coefficients,
1, 2, 3 – vertices.

Solving above equation yields an overall formula describing linear changes of SLP within the triangle i.e.:

$$SLP = ax + by + c$$

This provides the information on the SLP gradient in x and y axes directions (and locally W-E and N-S axes respectively) and thus directly yields the horizontal SLP gradient $dp/dl=\sqrt{(a^2+b^2)}$ and its direction (via arctan function). It allows the geostrophic wind speed (V) calculations with the above presented formula. The calculations assume the linear changes of SLP within the triangle and the V value is adjusted to air density which is calculated via the utilization of interpolated SLP and t_{995} values at the tangential point.

The calculations for the period 1951-2014 with the temporal resolution of 6 hours provided over 90 000 values of V, u and v. Such sample size - even for individual months (>100 observations) and years (>1200 observations) allows effective estimation of statistical characteristics.

Overall annual cycle of geostrophic wind vector characteristics was described with averages and quantiles: 1% and 99% which allowed additional insight into the seasonal structure of extreme values. Also, the coefficient of wind direction stability (η) was calculated with the utilization of the following formula:

$$\eta = \frac{\sqrt{\bar{u}^2 + \bar{v}^2}}{\bar{V}}$$

where:
η - coefficient of wind direction stability,
u - average value of zonal geostrophic wind component,
v - average value of meridional geostrophic wind component,
V - average value of geostrophic wind speed.

Above analysis was further aided by the directional structure analysis for the whole period as well as individual decades. Multiannual variability analysis comprised the trend analysis of monthly averages of V, u and v together with their monthly quantiles (10% and 90%). The difference from the overall annual cycle analysis (performed with 1% and 99% quantiles) stems from the fact that the number of cases in individual months varies from 112 to 124 and the utilization of such extreme quantiles might have led to unsatisfactory estimation of desired characteristics. Thus, it was decided that in the case of multiannual trend analysis less extreme (10% and 90%) quantiles will be used as a measure of temporal variability of extreme values - also recommended by IPCC in SREX report as a measures of occurrence of climate/weather extremes (IPCC 2012). All trend equations were tested for significance at α=0.05 significance level with the F-Snedecor test.

Analysis of extremes also comprised the application of GEV (Generalized Extreme Value) distribution. It was fitted to maximum annual/monthly values of wind speed (V_{max}) adopting the block maxima approach. GEV distribution can be defined with following formulas (Coles 2001; Gilleland and Katz 2014).
GEV PDF (Probability Density Function):

$$f(x,\mu,\sigma,\xi) = \frac{1}{\sigma} t(x)^{\xi+1} e^{-t(x)}$$

$$t(x) = \begin{cases} \left(1 + \left(\frac{x-\mu}{\sigma}\right)\xi\right)^{-1/\xi} & \text{if } \xi \neq 0 \\ e^{-(x-\mu)/\sigma} & \text{if } \xi = 0 \end{cases}$$

where:
μ - location parameter,
δ - scale parameter,
ξ - shape parameter.

and GEV CDF (Cumulative Distribution Function) with:

$$F(x;\mu,\sigma,\xi)=\exp\left\{-\left[1+\xi\left(\frac{x-\mu}{\sigma}\right)\right]^{-1/\xi}\right\}$$

where:
μ - location parameter,
δ - scale parameter,
ξ - shape parameter.

GEV CDF allows the estimation of so called return level (z_p) which can be defined as the value that will be exceeded every 1/p periods where 1-p is the assigned probability associated with the GEV distribution quantile (Gilleland and Katz 2014). We search for the values z_p, that $F(x_p)=1-p$. If we assume that $y_p= -1/\ln(1-p)$ then z_p equals (Gilleland and Katz 2014):

$$z_p=\begin{cases}\mu+\frac{\sigma}{\xi}\left[y_p^{\xi}\right], \text{if } \xi\neq 0\\ \mu+\sigma\ln y_p, \text{if } \xi=0\end{cases}$$

The GEV analysis was performed with the usage of R statistical computing software and „extRemes 2.0" package. In the GEV parameters estimation MLE (maximum likelihood estimation) method was utilised (Gilleland and Katz 2014).

Results

Overall statistics and annual cycle

Annual average of geostrophic wind speed (V) equals 7.4 ms^{-1} with the value of 99% quantile at 21.0 ms^{-1} (Table 1). Average zonal (u) and meridional (v) components equal 1.8 ms^{-1} and 0.7 ms^{-1} respectively. Overall extremes (1% and 99% quantiles) equalled -11.9 ms^{-1} (u) and -11.9 ms^{-1} (v) and 19.2 ms^{-1} (u) and 13.9 ms^{-1} (v) respectively. Maximum recorded value was 37.6 ms^{-1} (135.4 kmh^{-1}) and occurred 12th Feb 1962 at 12:00UTC.

V and geostrophic wind vector components' (u, v) characteristics exhibit a distinctive annual cycle (Table 1). In case of velocity the monthly averages range from 5.2 ms^{-1} (August) to 9.9 ms^{-1} (January) and only slightly less in December (9.7 ms^{-1}). Generally, from November to January the average monthly geostrophic wind speed exceeds 9 ms^{-1}. In spring (March/April) there occurs a substantial drop in V by 1.7 ms^{-1} (from 8.5 ms^{-1} to 6.8 ms^{-1}). During summer months V is the lowest in an annual course with values slightly exceeding 5 ms^{-1}. In autumn there is an increase as V exceeds 9 ms^{-1} again though this increase is not as rapid as in the case of the spring decrease. Extreme values of geostrophic wind velocity (99% quantile) range from 13.3 ms^{-1} (July) to 24.6 ms^{-1} (January). From April until September V_{max} values are lower or only slightly exceed 25 ms^{-1}. This part of the year clearly diverges from the remaining months.

Zonal component of geostrophic wind vector (u) ranges from -1.2 ms^{-1} (May) to 5.1 ms^{-1} (December). Generally, from April until June the negative values of u indicate the prevalence of eastern advection over the area of research whereas the rest of the year is dominated by westerly flow, though during July and August this domination is not clearly marked with the u averages at only 0.7 ms^{-1}.

Extreme values of zonal component (u) range from -14.1 ms^{-1} in March to -9.0 ms^{-1} in August (1% quantile) and from 10.4 ms^{-1} in May to 23.1 ms^{-1} in January (99% quantile).

Meridional component of geostrophic wind vector (v) exhibits much lower variability and it ranges from -1.1 ms^{-1} (June) to 2.2 ms^{-1} (November). From May until August negative values indicate the average advection from the northern sector. Extreme values range from -13.9 ms^{-1} in January to -9.0 ms^{-1} in August (1% quantile) and from 7.2 ms^{-1} in July to 16.2 ms^{-1} in January (99% quantile).

The monthly course of average wind direction stability (η) also reveals annual cycle. The highest values are recorded in January and December (exceeding 0.50) whereas the lowest in April (0.10) and August (0.14). Generally spring and summer months exhibit the lowest values not exceeding 0.25. Average annual η equals 0.26.

When inspecting the seasonal variability of the geostrophic wind vector components (u, v) there is an apparent difference in overall shape of their joint distribution (Fig. 2). In winter the variability is the greatest with the IQR (Inter Quantile Range - covering mid 50% of variability) at 10.5 ms^{-1} (u) and 8.6 ms^{-1} (v). Those values drop in spring to 8.1 ms^{-1} and 6.7 ms^{-1} respectively. Further drop is recorded in summer when the IQR values are nearly half of the of winter ones reaching 6.2 ms^{-1} (u) and 5.2

Table 1. Monthly and annual characteristics (ave – average, q_{01} – 1% quantile, q_{99} – 99% quantile, max - maximum) of geostrophic wind vector components (u – zonal, v – meridional) and velocity (V), η – wind direction stability coefficient, 1951-2014

Month/ Characteristics		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	YEAR
V	ave	**9.9**	**8.9**	**8.5**	**6.8**	**5.8**	**5.3**	**5.3**	**5.2**	**6.5**	**7.9**	**9.3**	**9.7**	**7.4**
	q_{99}	24.6	23.0	21.2	17.0	13.5	13.6	13.3	13.5	16.9	19.8	22.6	24.5	21.0
	max	36.0	37.6	28.8	25.4	20.9	18.0	23.1	23.9	25.4	31.0	32.5	34.4	37.6
u	q_{99}	23.1	21.4	19.3	14.1	10.4	11.1	11.6	11.6	15.0	17.9	21.6	22.9	19.2
	ave	**4.8**	**2.8**	**1.5**	**-0.5**	**-1.2**	**-0.1**	**0.7**	**0.7**	**1.7**	**2.7**	**3.8**	**5.1**	**1.8**
	q_{01}	-12.1	-12.6	-14.1	-13.0	-11.5	-10.4	-10.1	-9.0	-10.3	-11.6	-12.0	-12.1	-11.9
v	q_{99}	16.2	15.4	14.4	12.2	9.1	7.5	7.2	8.6	11.2	15.2	16.0	14.9	13.9
	ave	**1.5**	**1.3**	**1.1**	**0.5**	**-0.1**	**-1.1**	**-1.0**	**-0.1**	**0.4**	**1.7**	**2.2**	**1.6**	**0.7**
	q_{01}	-13.9	-13.1	-13.0	-12.0	-9.6	-10.0	-9.2	-9.0	-11.1	-11.8	-13.3	-13.0	-11.9
η		**0.51**	**0.35**	**0.22**	**0.10**	**0.21**	**0.21**	**0.23**	**0.14**	**0.27**	**0.40**	**0.47**	**0.55**	**0.26**

ms^{-1} (v). This is also clearly depicted in the values of joint probability distribution. In autumn the IQR values do not deviate far from the spring ones. Winter median values indicate greater share of western advection with values 4.1 ms^{-1} (u) and slight prevalence of southern indicated by 1.4 ms^{-1} median value for v. In spring this changes as the u median is slightly negative (-0.4 ms^{-1}). In summer the u median is positive but the value is much lower than in winter (0.3 ms^{-1}). This is accompanied by the change of sign in the case of v median which turns to negative (-0.8 ms^{-1}). In autumn there is an increase of the u median values (2.4 ms^{-1}) whereas for the v component the value is even greater than in winter (1.5 ms^{-1}) clearly indicating the prevalence of the advection from the southern sector.

Figure 3 reveals clear annual cycle in the geostrophic wind directional structure over Poland.

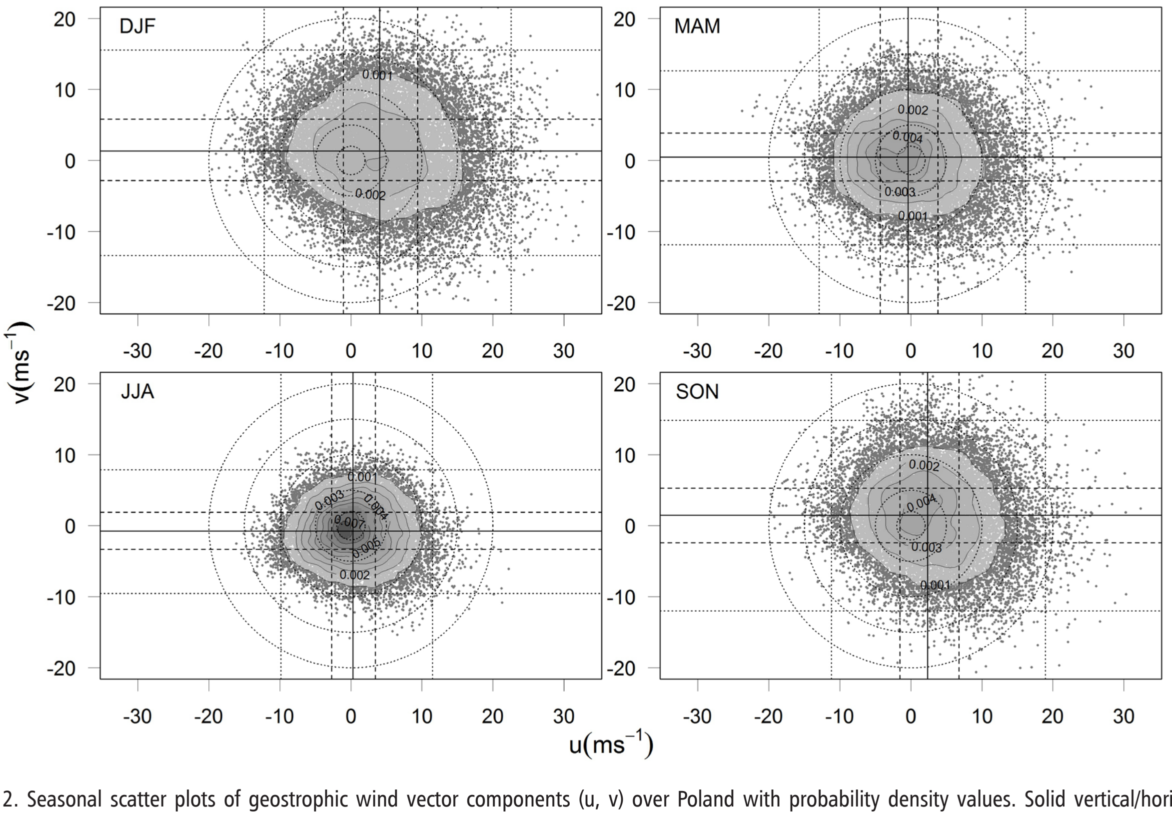

Fig. 2. Seasonal scatter plots of geostrophic wind vector components (u, v) over Poland with probability density values. Solid vertical/horizontal lines – median, dashed vertical/horizontal lines – 25% and 75% quantiles, dotted vertical/horizontal lines – 1% and 99% quantiles. Velocity circles at: 2, 5, 10, 15 and 20 ms^{-1} 1951-2014

From September to February there is a marked dominance of advection from the western sector with the frequencies (for individual directions) exceeding 10%. In total sector from SW to NW comprises 57% of all cases in December, 55% in January and 46% in November. Other sectors' frequencies rarely exceed 5%. Such structure changes quite rapidly in spring when there occurs a significant shift towards the prevalence of the eastern sectors with direction frequencies around 10% in April and May. This feature continues toward summer months however in July western (WNW and NW) sectors start to constitute a greater share in the overall directional structure. In general, July and August are the months of relative balance between the easterly and westerly advection (this is also reflected in the values of wind direction stability during this part of the year). During summer the increased share of easterly directions gradually diminishes and from September the westerly advection dominance is re-established.

Characteristics for the 1951-2014 period provide only the most general view of the directional structure of the airflow over Poland. When investigating in decadal scale (Fig. 4) differences are evident showing that the structure is not stable. In comparison with 1951-2014 decade 1951-1960 exhibited greater share of eastern sector directions in spring and early summer with the differences exceeding (+4%) in June and April. Also, there is

Wind direction	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
N	3.0	4.0	3.6	4.3	4.8	7.0	6.1	4.6	4.4	3.3	2.5	2.7
NNE	2.4	2.9	2.9	4.7	5.6	7.2	6.6	4.6	3.5	2.6	2.0	1.6
NE	1.8	2.9	2.6	6.0	8.6	8.2	7.1	5.3	4.0	2.2	1.5	1.6
ENE	2.5	3.3	4.2	8.0	10.5	8.8	8.3	7.1	4.6	2.5	2.2	2.5
E	3.9	5.0	6.2	9.2	9.5	7.9	5.8	6.5	4.8	4.2	3.4	3.7
ESE	3.8	5.6	8.3	8.7	7.9	5.7	4.8	6.5	5.4	4.4	3.8	3.6
SE	4.5	6.7	6.7	6.7	6.7	4.7	4.0	5.7	5.6	5.2	5.1	3.4
SSE	4.5	6.0	6.7	6.7	6.0	3.7	3.9	5.0	5.5	7.0	6.8	4.3
S	6.8	6.9	7.1	6.4	5.0	4.0	3.5	5.1	6.2	8.3	9.5	6.1
SSW	7.2	7.7	6.8	6.7	5.2	4.7	4.6	5.8	7.7	9.5	10.4	8.6
SW	10.0	8.0	7.3	6.2	5.4	4.8	5.4	6.8	8.4	10.6	10.8	11.2
WSW	13.1	8.9	8.1	5.3	4.6	5.2	6.6	7.3	8.3	9.7	10.8	13.8
W	13.1	10.1	8.5	5.9	4.9	5.9	8.2	7.5	8.3	10.0	11.3	13.5
WNW	11.5	10.3	8.8	5.2	5.4	7.2	8.8	8.0	8.8	9.1	9.9	11.7
NW	7.4	7.1	7.5	5.6	5.0	7.6	8.9	8.2	8.2	6.9	6.2	7.1
NNW	4.5	4.6	4.6	4.5	4.9	7.5	7.3	6.0	6.3	4.4	3.8	4.3

Month

Fig. 3. Monthly structure of geostrophic wind directions frequencies (%) over Poland 1951-2014

a frequency drop (by over 3%) in March and November (for the SW-WNW sector). In this decade the dominance of western sectors in colder part of the year is not so strongly marked as in the 1951-2014 period. Next decade (1961-1970) agrees with the overall characteristics with only minor diversions from the multiannual directional structure - increased share of eastern sector in summer and slightly decreased share of WNW and W sectors in December and January. 70-ties (1971-1980) clearly show increased share of SSE-SSW sector (+4%) in January and February with simultaneous drop by over 4% in the W-WNW share. In spring (April) there is a decrease in the S sector and at the same time increase in ENE sector's share. In winter (November and December) there is a visible increase in the western sector directions frequencies with the anomaly exceeding +7% (W in November). During 1981-1990 decade there is a considerable increase in the western sector frequencies in winter months. For NW it is also present in summer. In case of other months and sectors the anomalies do not exceed 3% except separated increases in March (SW, WSW), June (W), September and October (W). What strikes is the general negative anomaly during spring months for the eastern sector. The last decade of 20th century exhibits an increase in the western sector during winter months (January, February) with anomalies exceeding +7% in February (W). First decade of 21st century is quite similar to 1951-2014 period and only individual month/sectors frequencies anomalies exceed ±3%. What is visible though, is a slightly increased share of western sector in March with accompanying decrease in eastern sector. Also, there is an increase in SW share in summer (exceeding +2%). Above mentioned patterns are also reflected in Figure 8 presenting the multiannual variability of monthly u and v components. The dominance of westerly sectors in 80s and 90s clearly reflects the variability of atmospheric circulation in a broader spatial scale - NAO index and its positive phase. On the other hand 50s and 60s with their greater share of eastern advection and drop in western sectors share also coincide with NAO negative phase at this time (BAAC II 2015).

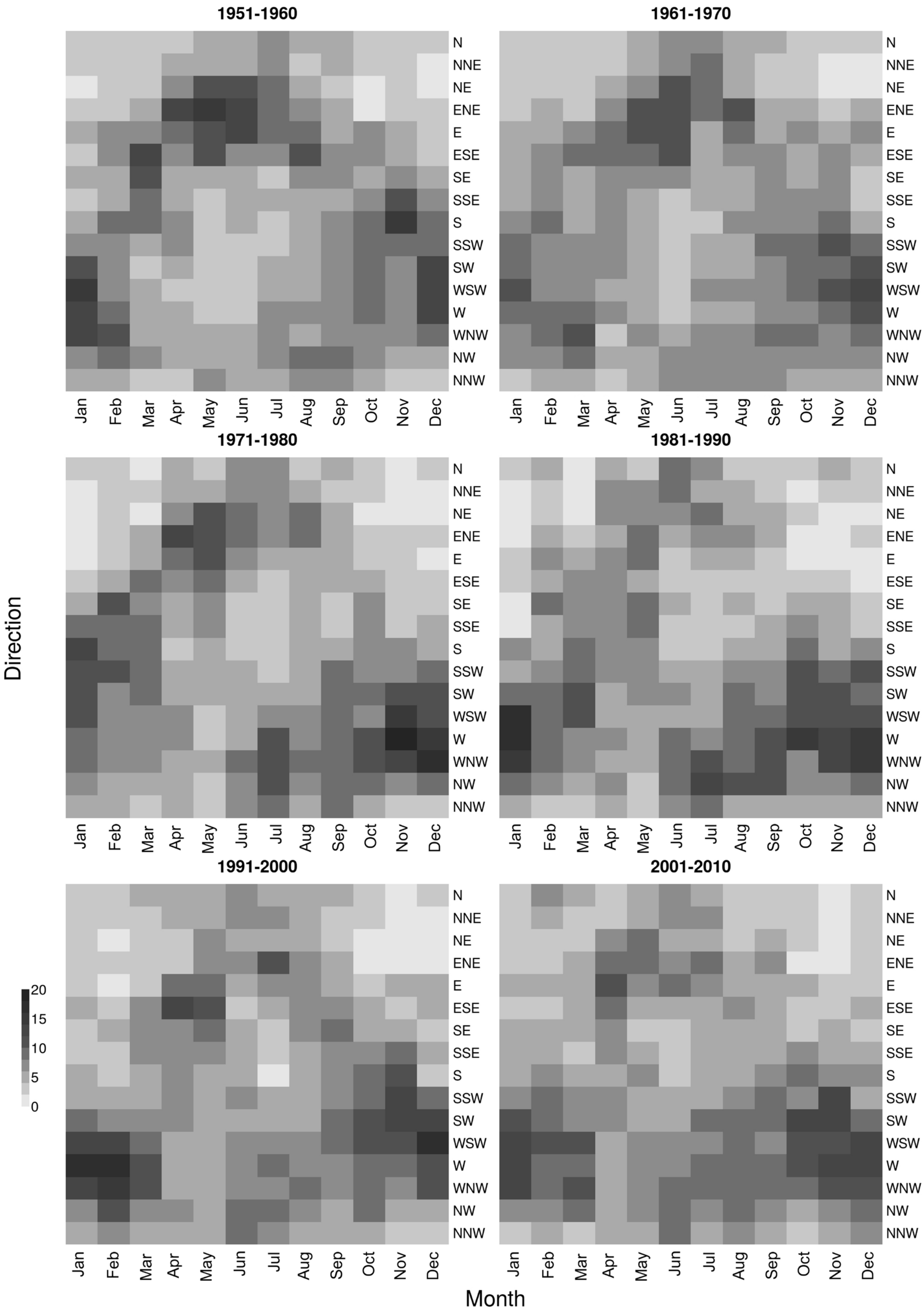

Fig. 4. Directional structure (%) for geostrophic wind over Poland in selected decades 1951-2010

Temporal variability

Multiannual variability of geostrophic wind and its components reveals some statistically significant trends (Table 2, Fig. 5). All trend equations were tested for significance at α=0.05 level with the F-Snedecor test. Only statistically significant changes are referred to as trend. In other cases tendency is mentioned. In case of annual averages/characteristics there is a significant positive trend (at α=0.05 level) in V 90% quantile value and geostrophic wind zonal component u (0.13 ms^{-1}/10y and 0.29 ms^{-1} /10y respectively). The trend coefficient for v component annual averages equals 7.58·10-5 ms^{-1}/10y (hence 0.00 in Table 2) and is not statistically significant. Trend coefficients of annual characteristics of geostrophic wind vector components are similar to the ones provided by Degirmendžić et al. (2004) (0.17 ms^{-1}/10y for u and 0.02 ms^{-1}/10y for v) and calculated for Central Europe. When inspecting the course of average annual V values (Fig. 5) there is only slight year-to-year variability with the range from 6.77 ms^{-1} (1952) to 8.06 ms^{-1} (1998). Extreme values (90% quantile) range from 11.86 ms^{-1} (1960) to 14.94 ms^{-1} (1993) and only slightly less in 2007 (14.88 ms^{-1}) with, as mentioned above, significant positive long term changes. The trend coefficient of annual Vmax values (0.33 ms^{-1}/10y) is not statistically significant.

For geostrophic wind components the variability of annual averages is higher (Fig. 6). As mentioned before in case of zonal component there is a significant positive trend and the highest u values were recorded in the mid 80-ties until late 90-ties which coincides with strong zonal flow over the continent

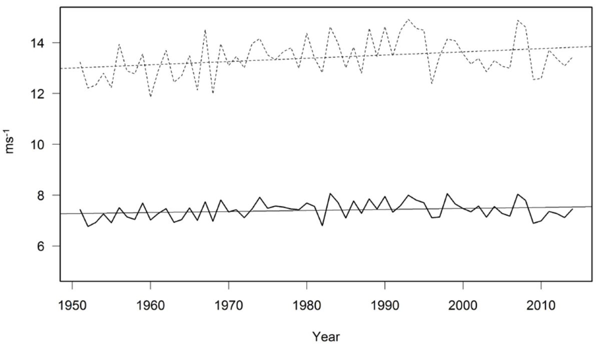

Fig. 5. Course of annual average (solid line) and 90% quantile (dashed line) values of geostrophic wind speed (ms^{-1}) over Poland 1951-2014

expressed by e.g. NAO index (BACC II 2015). Also, the course of u is to large extent concordant with the results of Degirmendžić et al. (2004) for broader spatial. From the last significantly marked maximum in 1998 (3.70 ms^{-1}) there is a visible downward tendency in the annual u vales however this period is also marked with high year-to-year variability. Overall, the range of the annual average u values equals 4.58 ms^{-1} with the highest value 3.95 ms^{-1} (1983) and the lowest -0.64 ms^{-1} (1963). Very low annual value was also reached in 1996 (-0.06 ms^{-1}). Annual extremes (10% and 90% quantiles) for the u component exhibit significant trends with coefficient 0.33 ms^{-1}/10y (10% quantile) and 0.29 ms^{-1}/10y (90% quantile). This indicates nearly the same pace for annual averages as well as extremes thus means the constant variability despite the overall increase in the u values.

The v component varies from -0.65 (1963) to 2.14 (1951) with the range of 2.79 ms^{-1}. Also in 2014 the value of v was one of the highest and differs considerably from the ones recorded in the first decade of 21st century. The recorded trends of annu-

Table 2. Trend coefficients (ms^{-1}/10y) of annual and monthly averages and quantiles (10% and 90%) of geostrophic wind vector components (u – zonal, v -meridional) and velocity (V) and stability coefficient (η/100y^{-1}) 1951-2014. Values significant at α=0.05 were bolded

	Month/ Variable	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
V	average	0.20	0.14	0.00	-0.09	-0.08	-0.02	-0.01	-0.02	0.07	**0.18**	-0.04	0.15	0.04
	q90	0.34	0.15	0.11	-0.14	-0.12	0.02	0.08	-0.03	0.05	**0.34**	-0.23	0.32	**0.13**
u	q10	0.13	0.45	0.36	0.22	**0.30**	**0.49**	0.14	**0.34**	0.02	0.19	0.38	0.31	**0.29**
	average	0.21	0.40	**0.48**	0.14	**0.35**	**0.51**	0.19	**0.30**	0.03	**0.33**	0.29	0.29	**0.29**
	q90	0.25	0.41	**0.53**	0.04	**0.40**	**0.53**	0.21	0.17	0.09	**0.46**	-0.02	0.35	**0.33**
v	q10	-0.19	-0.21	**-0.41**	-0.01	0.07	-0.04	0.17	0.16	0.09	0.15	0.13	-0.03	-0.02
	average	-0.10	-0.12	-0.28	0.02	0.09	-0.05	**0.16**	0.10	0.07	0.19	-0.03	-0.05	0.00
	q90	-0.02	-0.19	-0.27	-0.12	0.08	-0.01	0.11	0.07	0.12	**0.42**	-0.31	0.06	-0.04
η		0.12	0.01	-0.04	-0.16	**-0.39**	-0.12	-0.02	0.18	0.09	0.09	**0.22**	0.08	0.12

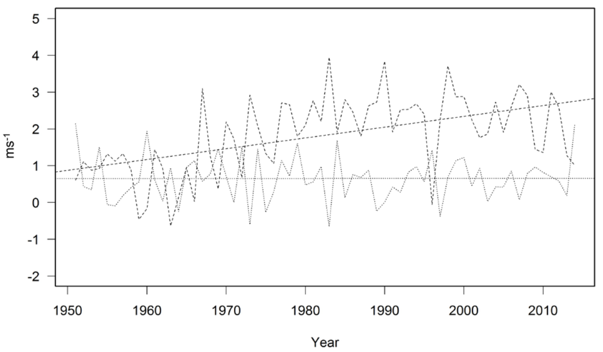

Fig. 6. Course of annual averages (ms-1) of geostrophic wind vector components: u – zonal: dashed line, v – meridional: dotted line, over Poland 1951-2014

al v values are not significant in case of all analyzed characteristics (averages and quantiles).

Course of monthly averages of the geostrophic wind speed seems relatively stable with the highest values recorded from November until March. In some cases V exceeds 15 ms-1 (e.g. 2007) and on multiple occasions is higher than 10 ms-1 especially in December and January (Fig. 7). The month with the highest recorded average geostrophic flow over Poland is January 2007 (15.3 ms-1). Generally from December until March the average monthly values of V over Poland exceed 6 ms-1 with the exception of February (1980, 1982) with 5.8 ms-1. January is a month with the highest overall variability with the overall values from 6.7 to 15.1 ms-1. The range of V values for November and December is only slightly lower (7.0 ms-1, 7.9 ms-1 respectively). In March the average monthly values of V are still above 6.0 ms-1 but the range of variability is reduced to 4.8 ms-1. In April there is a continuation of the drop in monthly average V values together with the range dropping again to 3.3 ms-1 which indicates the beginning of the part of the year when the overall V range is below 4 ms-1 (April – August) and the maximum recorded monthly averages do not exceed 8 ms-1 (May – August). Generally, in summer the V monthly averages vary from 3.3 to 7.2 ms-1 but 80% of mid variability range (difference between 90% quantile and 10% quantile) is below 2 ms-1 with the lowest values in June (1.7 ms-1) and only slightly higher on July and August (1.8 and 1.9 ms-1 respectively). In autumn there is a gradual return to the winter regime. In September there occurs an increase in overall variability with the range at 4.2 ms-1 with the maximum closing to 9 ms-1 (8.8 ms-1 in 1978). As we approach winter the increase in the overall variability is even more visible with the V range values exceeding 6 ms-1 (6.4 ms-1 and 7.0 ms-1 in October and November respectively). Maximum monthly average values exceed 10 ms-1 (October and November) and the absolute maxima were recorded in November 1973 (13.1 ms-1) and October 1999 (12.2 ms-1).

Monthly stability coefficients values exhibit large variability (Fig. 7). This is reflected in the range of the monthly values and results in an annual cycle with values from 0.65 (April) to 0.80 (October). When the mid 80% of variability (90% quantile –

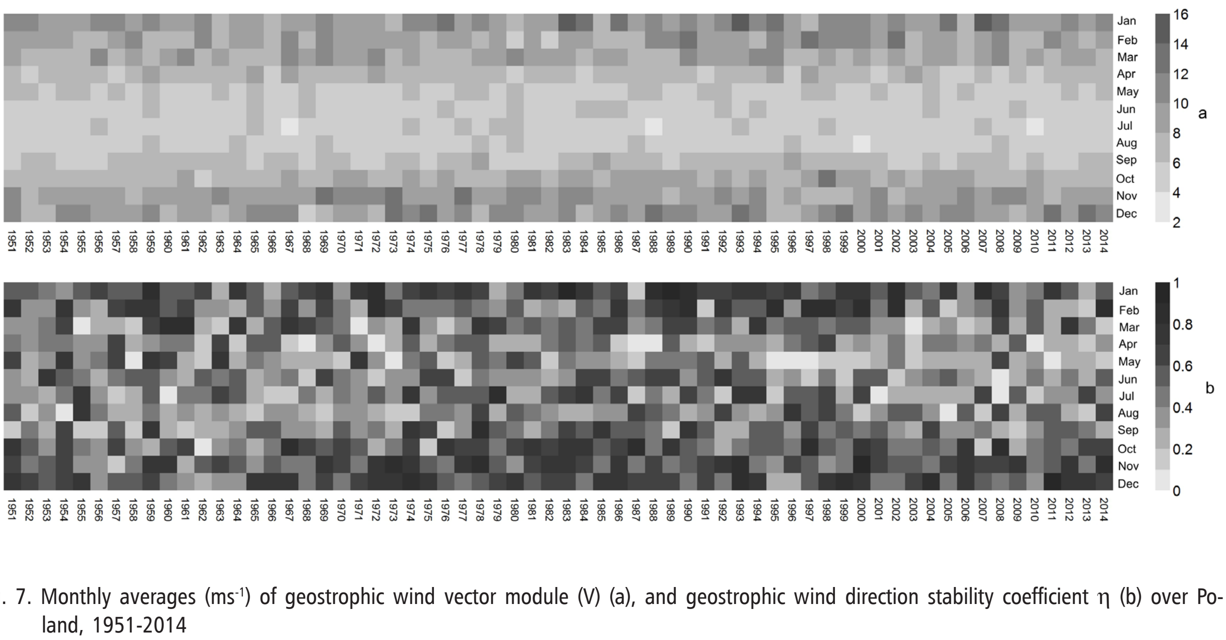

Fig. 7. Monthly averages (ms-1) of geostrophic wind vector module (V) (a), and geostrophic wind direction stability coefficient η (b) over Poland, 1951-2014

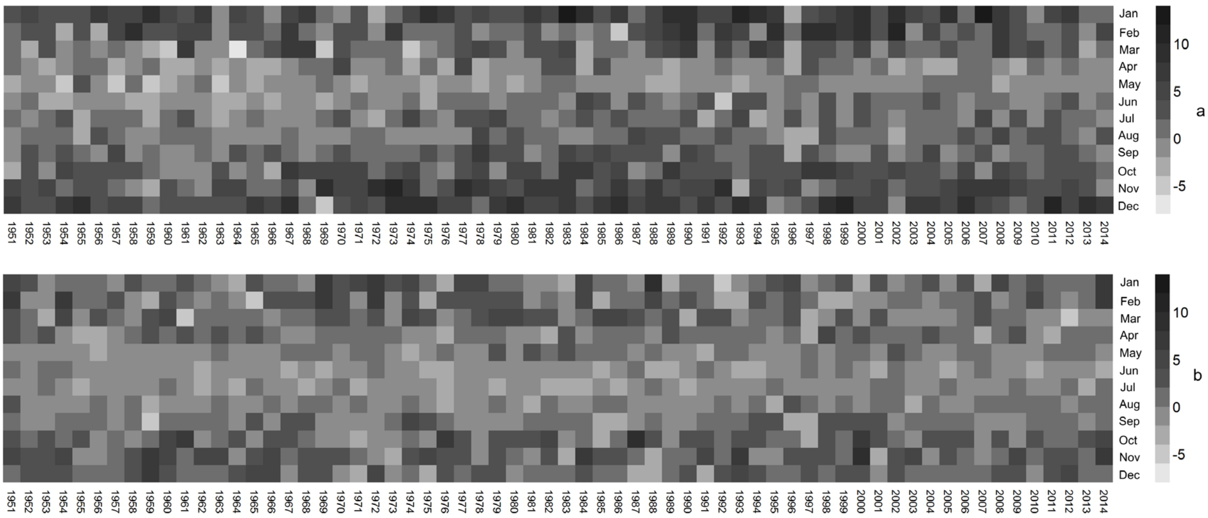

Fig. 8. Monthly averages (ms^{-1}) of geostrophic wind vector components: u (a), v (b) over Poland, 1951-2014

10% quantile) is considered, with values between 0.40 (December) to 0.53 (February), there is no distinguished annual cycle. This is well exhibited in Figure 7b. Overall structure is characterized by the prevalence of higher η values in the colder part of the year with the maxima exceeding 0.9 (0.92 in November 2000, 0.91 in January 1989) and the minima with values below 0.05 recorded in spring and summer (0.02 in July 2000, 0.03 in April 1987, May 1997 and August 2005).

Analysis of the course of V monthly averages and extremes does not reveal significant trends (Table 2) with the exception of October when there is a significant positive trend in both: average (0.18 ms^{-1} /10y) and 90% quantile of V (0.39 ms^{-1}/10y). Such discrepancy in the pace indicates increasing variance and resulting range of recorded values. From April until August there are negative V tendencies but the pace does not exceed 0.1 ms^{-1}/10y. Such situation is also present in November.

In the case of zonal geostrophic wind component (u) there is a marked domination of positive monthly trend coefficients and when it comes to averages there are statistically significant positive trends in March, May, June, August and October. Trend coefficients' values range from 0.03 ms^{-1}/10y (September) to 0.51 ms^{-1}/10y (June). Only slightly lower values are noted in March (0.48 ms^{-1}/10y).

In case of 10% quantile of zonal component (u) significant trends (also positive) are recorded only in three months: May, June and July with values 0.30, 0.49 and 0.34 ms^{-1}/10y respectively. In case of 90% quantile of u the situation is quite similar with positive trends in March, May and June as well as October. Highest values are recorded in March and June (0.53 ms^{-1}/10y). The overall shape of u variability suggests the shift towards the stronger western sector advection during almost the whole year. This may have a special significance for spring months which are usually associated with easterly flow. Here, the shape of long term variability suggest a gradual change in character of an air flow.

Meridional component (v) does not reveal as many significant trends (for individual months) as it was in the case of zonal component. Monthly averages exhibit significant trend only in July with the positive coefficient at 0.16 ms^{-1}/10y. Generally, tendencies range from -0.28 ms^{-1}/10y in March to aforementioned 0.16 ms^{-1}/10y in July. V 10% quantile trend is significant only in March (-0.41 ms^{-1} /10y) and in the case of v 90% quantile statistically significant positive trends are recorded only in October (0.42 ms^{-1}/10y).

Stability coefficient reveals clear annual cycle of trend coefficients with positive values from August until February and negative in the remaining months (March-July). However, only in May and November trends are statistically significant reaching at the same time the highest absolute values:

-0.39/100y and +0.22/100y in May and November respectively.

GEV analysis

One of the most important applicative aspects in the wind speed analysis is the analysis of extreme values. Figure 9 presents the course of annual geostrophic wind speed maxima (V_{max}). They range from just above 20 ms^{-1} (1952) to over 35 ms^{-1} (1962, 2007). There is no significant trend in the recorded annual maxima course (trend coefficient equals 0.33 ms^{-1}/10y). Stationary GEV was fitted (block maxima approach) allowing the estimation of return levels (RL) values for desired return period together with the 95% confidence range. Despite the fact that there seems to be a trend in the annual V_{max} values the calculated trend coefficient is insignificant (at α=0.05 level). Still, there appears to be a difference in the overall level of V_{max} during sub-periods: 1951-1980 and 1981-2014. This is somehow confirmed in Figure 10 - quantile-quantile plot for the aforementioned periods thus allowing the direct comparison of their V_{max} distributions. The results show that in the case of lower V_{max} quantiles there is a steady (along the distribution) difference of approx 2 ms^{-1}. This is most visible in the mid quantiles of the distribution and diminishes towards the upper tail. Still, the overall stationarity of the series allowed the fitting of stationary GEV. With reference to annual maxima results (Fig. 11) of GEV fitting show that for 10 year return period expected

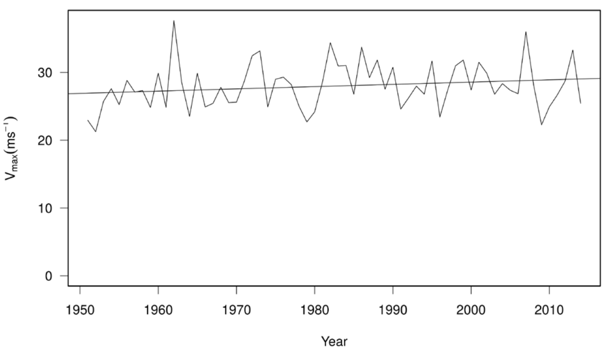

Fig. 9. Course of annual maxima of geostrophic wind speed (ms^{-1}) over Poland, 1951-2014

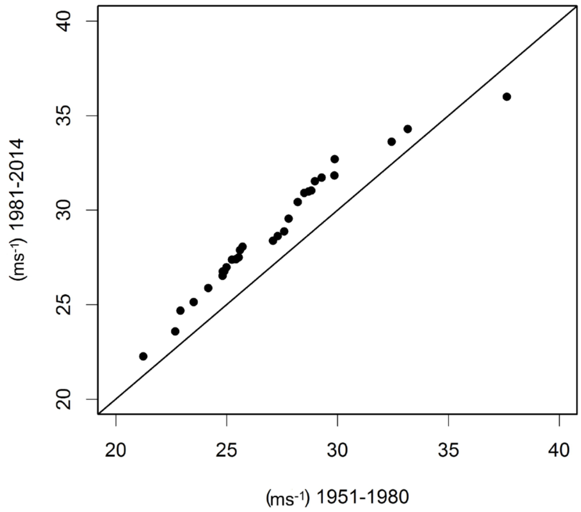

Fig 10. QQ-plot of maximum annual geostrophic wind velocity over Poland for sub periods: 1951-1980 and 1981-2010

(the one that shall be exceeded) RL value is 32 ms^{-1} with a range of uncertainty between 30 and 34 ms^{-1}. For 100 year return period the estimated RL value equals 37 ms^{-1} with the range from 33 ms^{-1} to 39 ms^{-1}.

Additionally, individual months Vmax values were analyzed with respect to the existence of statistically significant trends. Except from October none of the months exhibits statistically significant trends. This allowed the further GEV analysis providing insight into the annual structure of the return period values together with the estimation of uncertainty at 95% confidence level (Table 3).

From November until February even for 2y return periods RL values exceed 20 ms^{-1} with the upper estimation reaching nearly 25 ms^{-1}. For longer return periods values rise significantly and in the case of 50y and 100y return periods estimation of RL for those months exceeds 30 ms^{-1} with the upper 95% confidence boundary exceeding 38 ms^{-1} in January and being only slightly lower in December and February (36.9 ms^{-1} and 37.6 ms^{-1} respectively). Return levels drop significantly in the warmer part of the year. In April only return levels for over 10y return periods exceed 20 ms^{-1} and from May until August only for 50y and 100y return levels the values are higher than 20 ms^{-1} with maximum in July (21.8 ms^{-1} for 100y return period). Even when looking into upper estimates (at 0.95 confidence level) only in July (for 100y return period) they exceed 25 ms^{-1}. This clearly shows that there is a significant division of the annual cycle with respect to return

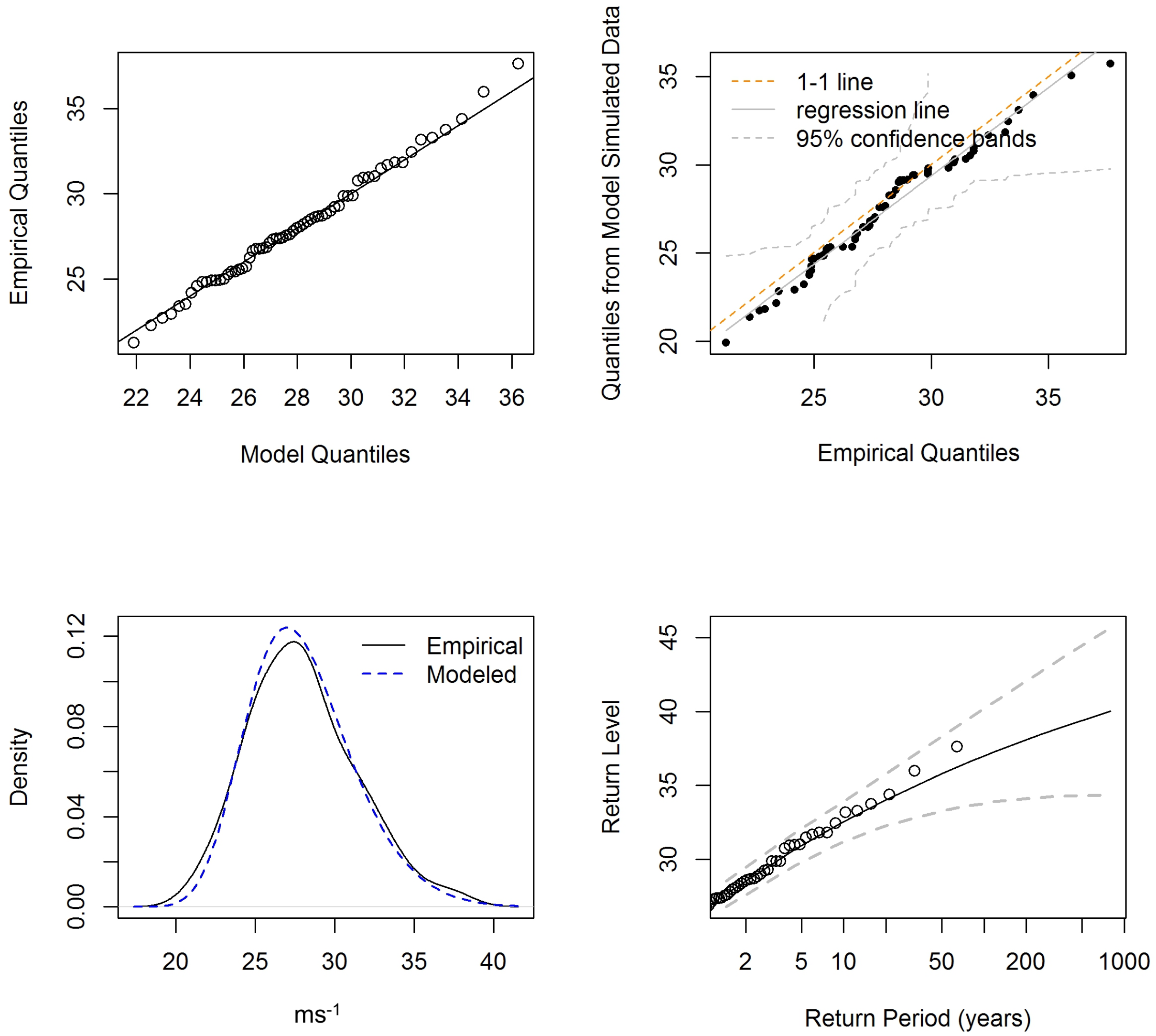

Fig. 11. GEV distributions diagnostic plots for annual maximum geostrophic wind speed based on fitted distribution parameters, 1951-2014

levels and in the overall picture the winter season values dominate in the shaping of Vmax GEV distribution.

Summary

It was confirmed that geostrophic wind vector can serve as an objective measure of the airflow characteristics over Poland. It provides detailed information about air flow intensity and direction which in conjunction with well documented homogeneity and availability of long time series of SLP in many areas allows multiannual analysis which in turn assures greater confidence in the estimation of the statistics. What must be stressed here is the fact that V is the theoretical wind speed not accounting for friction and the in-situ wind speed values might be lower depending on the surface roughness. The same applies to the flow direction which in the northern hemisphere will be diverted counter clockwise in comparison with geostrophic wind vector. Still, while taking this into consideration geostrophic wind may serve as a reliable measure of air flow which was exemplified in the aforementioned publications. For the period 1951-2014 average geostrophic wind velocity over Poland equals 7.4 ms^{-1} and the 99% quantile exceeds 21 ms^{-1}. Maximum speed ever recorded equalled 37.6 ms^{-1}. Geostrophic wind vector module (V) and its components (u, v) exhibit clear annual cycle with the

Table 3. Monthly return levels (RL) (ms^{-1}) of Vmax over Poland together with upper (U) and lower (L) boundaries of 95% return level confidence intervals, 1951- 2014

Month	Jan			Feb			Mar			Apr			May			Jun		
Return period (years)	L	RL	U	L	RL	U	L	RL	U	L	RL	U	L	RL	U	L	RL	U
2	22.5	23.7	24.9	20.2	21.3	22.4	19.1	20.3	21.5	15.9	16.6	17.3	12.4	13.0	13.5	12.2	12.8	13.4
5	26.2	27.6	29.0	23.8	25.3	26.7	22.5	23.8	25.0	18.2	19.1	20.1	14.2	15.0	15.7	14.0	14.7	15.4
10	28.2	29.8	31.4	25.8	27.6	29.4	24.2	25.6	27.0	19.4	20.7	21.9	15.2	16.2	17.2	14.9	15.8	16.7
20	29.6	31.6	33.6	27.5	29.7	31.9	25.3	27.1	28.9	20.4	22.0	23.7	16.0	17.3	18.7	15.4	16.8	18.2
50	30.9	33.6	36.4	29.1	32.1	35.1	25.9	28.6	31.3	21.2	23.7	26.2	16.8	18.7	20.7	15.7	18.0	20.2
100	31.5	34.9	38.3	30.0	33.8	37.6	26.1	29.6	33.1	21.6	24.9	28.2	17.1	19.7	22.3	15.7	18.8	21.9
Month	Jul			Aug			Sep			Oct			Nov			Dec		
2	11.8	12.6	13.3	12.0	12.6	13.2	14.6	15.3	16.1	18.6	19.5	20.3	20.4	21.4	22.5	22.2	23.5	24.8
5	14.2	15.2	16.2	14.1	14.9	15.8	17.1	18.2	19.3	21.5	22.6	23.8	23.8	25.1	26.4	26.2	27.6	28.9
10	15.6	16.9	18.2	15.3	16.4	17.6	18.5	20.1	21.6	23.1	24.6	26.0	25.6	27.3	28.9	28.2	29.7	31.2
20	16.6	18.4	20.2	16.3	17.8	19.4	19.6	21.9	24.1	24.4	26.3	28.2	27.0	29.2	31.4	29.6	31.4	33.1
50	17.7	20.4	23.1	17.3	19.6	21.9	20.6	24.2	27.8	25.7	28.3	31.0	28.3	31.5	34.6	30.8	33.1	35.4
100	18.3	21.8	25.3	17.9	20.9	23.8	21.0	25.9	30.9	26.4	29.8	33.1	29.0	33.0	37.0	31.4	34.2	36.9

highest V values in winter. Positive (westerly) u values dominate in the colder part of the year. In spring the dominance of eastern advection appears and in summer the prevalence of westerly flow is only minimal. Multiannual directional structure is not stable which is evident in the decadal analysis. In some cases the frequency anomalies exceed ±5% in individual sectors (and over 15% in adjacent multi-sector totals), what strikes in this case is the substantial increase in the share of western sector in the 1981-1990 decade. This is especially visible in winter and is continued at even greater scale during the next decade.

The analysis of extreme values of geostrophic wind speed, despite the fact that annual and monthly (with the exception of October) V_{max} values do not exhibit significant trends, revealed slight positive shift in the compound distribution during the second part of the analysis period (1981-2014) in comparison with the first thirty years of analysis (1951-1980). The shift is apparent along the nearly whole V_{max} distribution. GEV distribution allowed the estimation of return levels of geostrophic wind speed. The year can be divided into two parts. Warm part with relatively low return levels – for many months not exceeding 20 ms^{-1} even for 50y return period. On the other hand winter months return level values exceed 30 ms^{-1} even for relatively short return periods (20y) with upper estimates for 100y return period closing to 40 ms^{-1}. This indicates relatively frequent possibility of occurrence of extremely strong winds which results might be devastating to both population and infrastructure. Despite non existence (except from October) of statistically significant trends in the monthly averages' course of geostrophic wind speed annual V averages exhibit positive trend with the coefficient 0.13 ms^{-1}/10y. V trends for extremes are not significant – both: 90% V quantile and annual V_{max} with tendencies at 0.13 ms^{-1}/10y and 0.33 ms^{-1}/10y respectively. In the case of zonal component there is a significant positive change in the annual averages but also in annual extremes. What strikes is the same pace of change which indicates no change in the overall variability. This is accompanied by positive tendencies in all months. Spring (Mar, May) and summer (Jun, Aug) months exhibit significant positive trends in both averages and V 90% quantile but yet again the pace of changes does not diverge from each other. There are virtually no significant changes in the meridional component values indicating the lack of change towards neither southern or northern advection.

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