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Spatial and temporal variability of mean daily wind speeds in the Czech Republic, 1961–2015

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ABSTRACT: This contribution analyses the spatio-temporal variability of mean daily wind speeds (MDWSs) over the territory of the Czech Republic in the 1961–2015 period, using series from the 119 meteorological stations of the Czech Hydrometeorological Institute. These series were quality-controlled and homogenised by application of the standard normal homogeneity test, after Alexandersson, and the Maronna and Yohai test. The spatial variability of MDWSs is analysed in terms of annual and seasonal data, which exhibit a clear relationship to orographic character, with the highest values in highland and mountain areas. Spatial relationships between stations are interpreted by means of correlation graphs, which express the dependence of MDWSs on the altitude of the stations and the distance between them. Analysis of monthly, seasonal and annual linear trends for 4 altitudinal intervals and the entire Czech Republic shows a decreasing tendency, almost statistically significant (significance level of $\alpha = 0.05$). Taking the 119 stations individually, a certain proportion of stations also displays positive trends. Comparison of MDWS variability with circulation indices shows a closer relationship to the Central European Zonal Index than to the North Atlantic Oscillation Index. The results obtained are discussed with respect to problems associated with wind speed measurements, particularly the change from standard to automatic wind speed measurements, and a broadly occurring decline in measured wind speed series in recent decades ('wind stilling').

KEY WORDS: Mean daily wind speed · Spatial variability · Temporal variability · Wind stilling · Czech Republic

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1. INTRODUCTION

Studies of wind speed data often arise out of interest in extreme values (or wind gusts), those that involve loss of human lives or great material damage (Ulbrich et al. 2001, 2013, Fink et al. 2009, Stucki et al. 2014), and also with respect to their importance to the insurance industry (Della-Marta et al. 2010, Karremann et al. 2014, Zimmerli & Renggli 2015, Welker et al. 2016). More positively, knowledge of wind speed fields is essential to the effective operation of wind power stations (Hanslian et al. 2012, Hostýnek et al. 2012, Hanslian & Hošek 2015). However, despite the practical importance of wind speed data, the numbers of studies addressing the climatological nature of wind speed are much lower than those dedicated to temperature or precipitation.

Among other reasons for this dearth of studies may be the problems with wind speed measurements that lead to inhomogeneities in timeseries (Trenberth & Owen 1999), something difficult to remove with respect to weak spatial correlations between individual stations. Although some first attempts have been made, homogenisation of wind speed series has

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heretofore been less routine than that of other meteorological variables (e.g. Usbeck et al. 2010, Péliné Németh et al. 2011, 2014, Štěpánek et al. 2011). One problem is the creation of reference series with strong relationships to the series under consideration. Simulation of such reference series by mesoscale models may be a promising approach, as has been shown for wind-speed/gust series for stations over the Iberian Peninsula (Azorin-Molina et al. 2014, 2016). Use of homogenised wind speed series is a key requirement, particularly for the study of their temporal variability and for the calculation of long-term trends.

The latter factors are closely involved with the study of 'global stilling', a term coined to denote the decline in series of wind speeds recognised in various parts of the world, such as North America (Pryor et al. 2009, Pryor & Ledolter 2010), Australia (McVicar et al. 2008), Asia (Guo et al. 2011, Xiaomei et al. 2012, Chen et al. 2013, Kim & Paik 2015) and Europe (Smits et al. 2005, Brázdil et al. 2009, 2017, Azorin-Molina et al. 2014, 2016, Romani et al. 2015); for a global overview, see McVicar et al. (2012). These are also accompanied by studies attempting to provide explanations or reasons for such observed trends (Vautard et al. 2010, Bichet et al. 2012, Wever 2012, Xiaomei et al. 2012).

With respect to the Czech Republic, Sobíšek (2000) performed a comprehensive analysis of wind speeds over the territory of this land for 1961–1990. Employing 69 stations, he found negative or positive trends for approximately half of them; the mean annual wind speed trend from all stations stood at −0.068 m s^{-1} per 30 yr. Mean daily wind speeds (MDWSs) for 1961–2000 were also addressed in the climatic atlas of the Czech Republic (Tolasz et al. 2007), but without calculation of trends. Declining trends in series of mean wind speeds and maximum wind gusts were confirmed for a limited number of meteorological stations (22 and 19, respectively) in wind speed series extending from 1961 to 2005 (Brázdil et al. 2009) and from 1961 to 2014 for wind gusts (Brázdil et al. 2017).

The aim of this study was to analyse the spatiotemporal variability of MDWSs over the territory of the Czech Republic (up to 1993: Czechoslovakia) based on measurements taken in its dense network of 119 meteorological stations during the 1961–2015 period.

2. DATA

2.1. Wind speed data

The basis for the analysis of MDWSs consisted of 3 daily readings of wind speed (at 07:00, 14:00 and 21:00 h local mean time [LMT]) taken at 119 meteorological stations of the Czech Hydrometeorological Institute (CHMI) over the territory of the Czech Republic in the 1961–2015 period (Fig. 1; Table S1 in the Supplement at www.int-res.com/articles/suppl/c072p197_supp.pdf). Daily means were calculated as a simple arithmetical mean of the 3 daily readings and were taken from the CLIDATA database (Tolasz

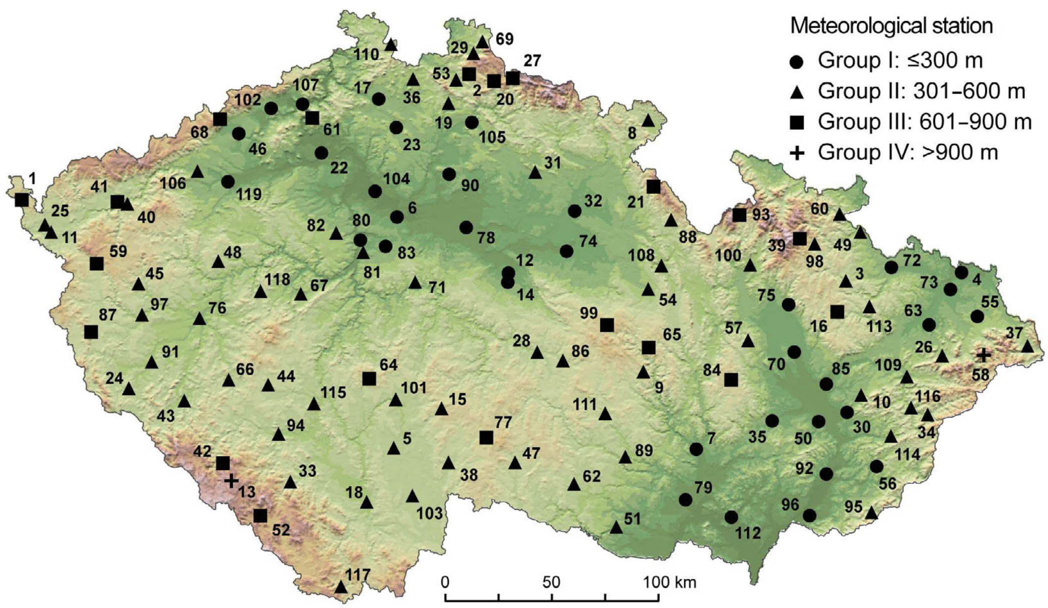

Fig. 1. Meteorological stations of Czech Hydrometeorological Institute used for study of mean daily wind speeds over territory of Czech Republic (for station names, coordinates and elevations, see Table S1 in the Supplement)

2009). The stations used cover the entire territory studied quite evenly and occupy various altitudinal positions, between the lowest, Ústí nad Labem station at 150 m above sea level (a.s.l.) (no. 107 in Fig. 1), and the highest, Lysá hora Mt. station at 1322 m (no. 58 in Fig. 1). On average, 1 station used corresponds to 662.7 km^2 of territory. Anemographs and anemo-indicators used to be the standard instruments, measuring wind speed at 10 min intervals (Řepka 2011), progressively superseded by automatic Vaisala wind sets from around the mid-1990s and further by ultrasonic wind sensors from the 2000s (Fig. S1 in the Supplement; for discussion and comparison of various wind speed measurements, see Section 5.1).

To address changes in wind speed arising out of altitude and features of the terrain, all stations were further divided into 4 groups, following the altitudinal division of morphometric types of relief of the Czech Republic according to Demek (1987):

Group I: 35 stations with altitudes <300 m, largely representing lowlands and flat, hilly lands

Group II: 62 stations between 301 and 600 m, consisting of flat and dissected hilly lands

Group III: 20 stations between 601 and 900 m, consisting of flat and dissected highlands

Group IV: only 2 stations (Churáňov and Lysá hora Mt.) at altitudes of >900 m, consisting of flat and dissected mountain positions

2.2. Circulation indices

To investigate relationships between MDWSs and large-scale atmospheric circulation, series of 2 such indices were used. The North Atlantic Oscillation Index (NAOI), calculated in several versions from pressure differences between the Azores High and Icelandic Low (e.g. Jones et al. 1997, Wanner et al. 2001, Trigo et al. 2002, Hurrell et al. 2003), is the most frequently used for the European area. NAOI data, after Jones et al. (1997), calculated as differences in normalised sea-level pressure between pressure series for Gibraltar (southwest Iberian Peninsula) and Reykjavik (southwest Iceland), were uploaded from the Climatic Research Unit's website: https://crudata.uea.ac.uk/cru/data/nao/. With positive NAOI values, the Czech territory is under the influence of westerly winds, with airflow from the Atlantic Ocean.

The second circulation index, the Central European Zonal Index (CEZI), is more appropriate to the Czech Republic, since the style of calculation is more representative for the territory (Jacobeit et al. 2001). CEZI is calculated as the difference in the standardised mean sea-level pressure, averaged for the grid points 35° N, 0°; 35° N, 20° E; 40° N, 0°; 40° N, 20° E; and 60° N, 0°; 60° N, 20° E; 65° N, 0°; 65° N, 20° E. High values of CEZI indicate a strong westerly flow from the Atlantic Ocean over Czech territory, while low CEZI values coincide with a weakening of westerlies.

Brázdil et al. (2009) demonstrated a number of mean wind speed relationships to both indices over the Czech Republic for the 1961–2005 period. Statistically significant positive correlation coefficients with NAOI were found for January, March, December, winter and autumn, while similar correlations for CEZI emerged for all months from November to March and July, and further for winter and spring. These results confirm the applicability of the 2 circulation indices to this study.

3. METHODS

Series of wind speed measurements for 119 selected meteorological stations in the 1961–2015 period were first qualitatively checked. Three approaches were taken to the detection of outliers in quality control (for more detail, see Štěpánek et al. 2011, 2013):

(1) Pairwise comparison, analysing differences in series between candidate (i.e. checked) and neighbouring stations

(2) Application of limits derived from interquartile ranges (either to individual series, i.e. absolutely, or to differences between candidate and reference series, i.e. relatively)

(3) Comparison of candidate series values (observed) with 'expected' (theoretical) values from 'technical' series created by means of statistical methods for spatial data (e.g. inverse distance weighting and kriging)

The relative homogeneity of MDWS series was tested by application of the standard normal homogeneity test (SNHT) by Alexandersson (1986) and the test by Maronna & Yohai (1978), following the methodology described in Štěpánek et al. (2011, 2013). Series from 6 stations with the highest correlations with the candidate series were used for reference and detection derived from the pairwise method (i.e. separately for each station). Breakpoints detected were then evaluated with respect to station metadata. Among the breakpoints not confirmed by metadata, only those which fulfilled the more rigorous criteria derived empirically from homogenisation experience were considered further (Štěpánek et al. 2013). Corresponding metadata were available for 51 % of all breakpoints detected. Adjustment of inhomogeneities on a daily scale was performed by the authors' adaptation of a method for the correction of regional climate model outputs by Déqué (2007), known as distribution adjustment by percentiles (DAP). Our procedure is based on comparison of percentiles (empirical distribution) of differences (or ratios) between candidate and reference series before and after a break. These steps—homogeneity testing, evaluation and correction of inhomogeneities detected—were performed in several iterations. Fig. 2 illustrates an example of the homogenisation procedure for annual MDWS series at the Hradec Králové station (no. 32 in Fig. 1). During the first iteration, 3 breakpoints were detected (one of them related to a change in the instruments used), while the second iteration showed 2 breakpoints (again, one related to a change in instruments). After quality control and homogenisation, missing data were filled in for MDWS series from the 119 meteorological stations (for more detail, see Štěpánek et al. 2013).

In order to describe the spatial variability of monthly, seasonal and annual MDWSs over the territory of the Czech Republic, correlation coefficients calculated among all 119 stations were presented in the form of box plots (see Fig. 3), as well as being expressed as correlation fields to address dependence on the distances between stations, and on their altitude (see Fig. 4). Further corresponding maps of MDWSs for seasonal and annual values were constructed on the basis of regression kriging (see Fig. 5). Interpolation was calculated by means of a digital elevation model at 500 × 500 m resolution, with each season and year treated individually. Predictors for the interpolation were selected with a view to statistical significance for a given season or year. Based on this approach, together with altitude, longitude, slope and 'topographic position index' (i.e. the roughness of the surface), predictors were applied in the same way for all seasons and year.

The temporal variability of monthly, seasonal and annual MDWS series of the 119 meteorological stations was characterised by calculation of linear trends for 4 altitudinal intervals and the entire Czech Republic (see Table 2, see Figs. 6–8). The *t*-test was used to evaluate the statistical significance of trends at a significance level of $\alpha = 0.05$.

The relationships of the monthly, seasonal and annual MDWS series from the 119 meteorological stations to atmospheric circulation, as expressed by NAOI and CEZI series in the 1961–2015 period, were investigated by calculating corresponding correlation coefficients for all stations, the 4 altitudinal groups and the entire Czech Republic (see Table 3, see Fig. 9). Statistical significance of the correlation coefficients was evaluated by a *t*-test at a significance level of $\alpha = 0.05$.

4. RESULTS

4.1. Spatial variability

The correlation coefficients between all 119 meteorological stations were calculated in order to describe the general spatial variability of MDWSs over the territory of the Czech Republic. The best inter-

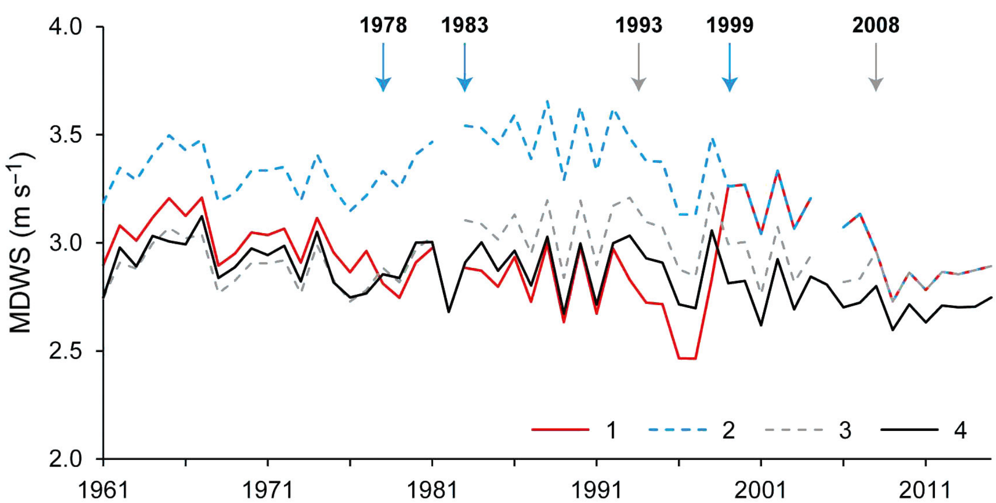

Fig. 2. Example of homogenisation of annual mean daily wind speeds (MDWS) series using standard normal homogeneity test at Hradec Králové station (no. 32 in Fig. 1): 1: measured data, 2: first iteration (breakpoints: 1978: no metadata, 1983: no metadata, 1999: Vaisala wind set), 3: second iteration (breakpoints: 1993: no metadata, 2008: Vaisala wind set re-calibration), 4: final series

relationships for monthly, seasonal and annual series of MDWSs expressed as box plots (Fig. 3) appear for January–February and DJF. On the other hand, the lowest correlation coefficients occur for May, August and JJA. Higher correlation coefficients in SON, compared to MAM and JJA, signal more strongly expressed circulation patterns in the winter half-year (October–March) compared to the summer half-year (April–September), when general circulation is weaker and more local effects (e.g. related to convection) occur frequently (Brázdil & Štekl 1986). However, some station couples exhibit negative correlation coefficients to a greater or lesser extent.

The interrelationships between the 119 meteorological stations for seasonal and annual MDWSs in Fig. 3 may be complemented by expression of correlation coefficients among them in terms of the distances separating stations (Fig. 4a) and on altitudinal differences between them (Fig. 4b). Simplification of correlation fields by linear regression lines indicates a general decrease of correlation coefficients with increasing distance (Fig. 4a), while, depending on the increasing altitude difference of stations, a similar effect is mildly expressed only in MAM; the other 3 seasonal and annual series show no such effect (Fig. 4b). Generally higher values in DJF (for distance between stations also in SON) signal the strongly expressed macro-circulation patterns during the winter half-year compared to the summer half-year, mentioned above (cf. Brázdil & Štekl 1986).

The geographical distribution of annual and seasonal MDWSs over the territory of the Czech Republic (Fig. 5) shows clear dependence on orography and altitude. The highest wind speeds are typical of northwest Bohemia (České středohoří Mts.), northern Bohemia (Krkonoše Mts.), the border area between Bo-

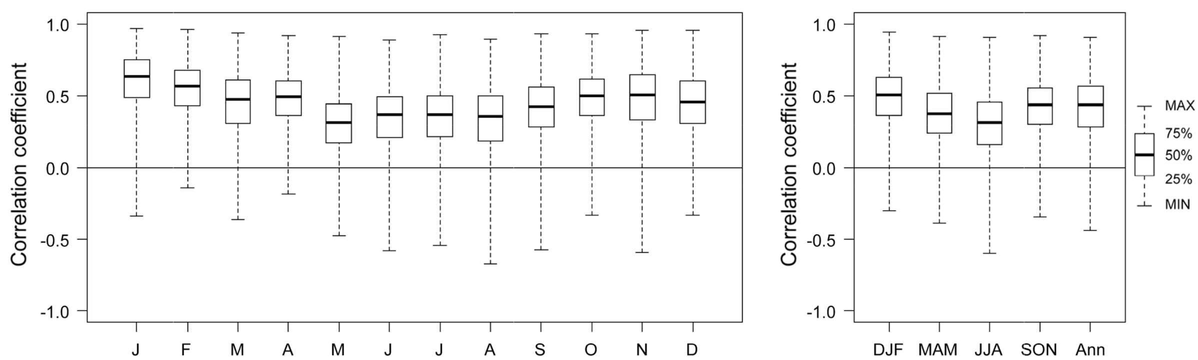

Fig. 3. Monthly, seasonal and annual correlation coefficients among mean daily wind speed series from 119 meteorological stations over territory of Czech Republic in 1961–2015 period

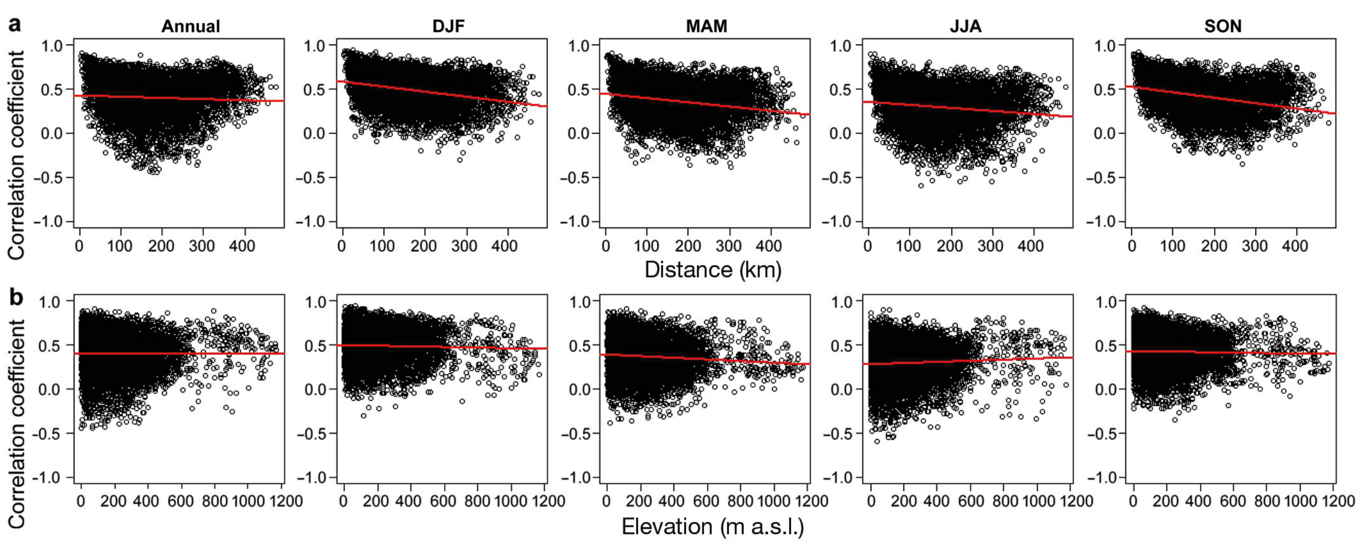

Fig. 4. Annual and seasonal correlation coefficients for mean daily wind speeds among 119 meteorological stations over territory of Czech Republic in 1961–2015 period with respect to (a) distances between them and (b) altitudinal differences. Regression lines appear in red

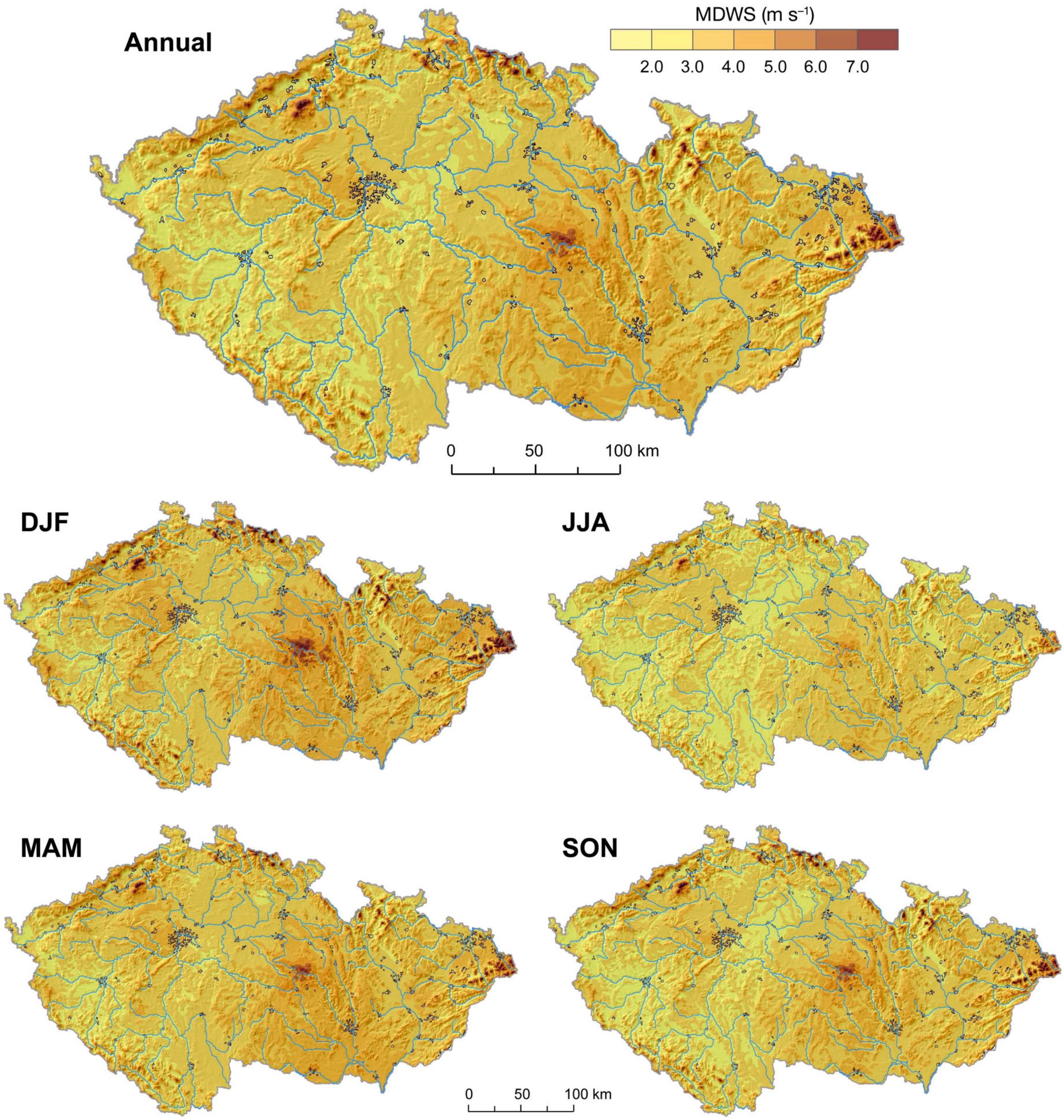

Fig. 5. Spatial distribution of mean annual and seasonal mean daily wind speed (MDWS) over territory of Czech Republic in 1961–2015 period

hemia and Moravia (north Bohemian-Moravian Highlands), northern Moravia (Hrubý Jeseník Mts.) and northeastern Moravia (Moravskoslezské Beskydy Mts.). The lowest wind speeds tend to occur in the lower positions consisting of valleys or basins. Such areas occur particularly in a broad belt around the southwest mountain range of Bohemia and then continue from south Bohemia to the north and then to the northeast; this is best expressed for JJA and SON (Fig. 5).

Table 1 shows the basic statistical characteristics of MDWSs in the year and individual seasons, as related to the maps in Fig. 5. Slightly more than half of the territory of the Czech Republic has annual and seasonal MDWSs between 2 and 3 m s^{-1}, except DJF. Nearly a third of the territory is characterised by MDWSs between 3 and 4 m s^{-1} in DJF and MAM, while in JJA this drops to wind speeds below 2 m s^{-1}. In SON, around a fifth of the territory has MDWSs below 2 m s^{-1} as well as wind speeds between 3 and 4 m s^{-1}. MDWSs in terms of the entire Czech Republic are highest in DJF (3.0 m s^{-1}) and lowest in JJA (2.3 m s^{-1}). Based on standard deviation, DJF values are the most spatially variable and JJA values the least. Lysá hora Mt. (1322 m a.s.l., no. 58 in Fig. 1)

Table 1. Area (%) of territory of Czech Republic with particular mean daily wind speeds (MDWSs) at various wind speed intervals, and mean, maximum and minimum MDWSs over Czech Republic in annual and seasonal series in 1961–2015 period

Year or season	Area (%) represented by MDWS interval							MDWSs (m s^{-1}) over the Czech Republic					
	<2 m s^{-1}	2–3 m s^{-1}	3–4 m s^{-1}	4–5 m s^{-1}	5–6 m s^{-1}	6–7 m s^{-1}	>7 m s^{-1}	Mean	SD	Station	Max	Station	Min
Annual	15.9	54.6	24.5	3.8	0.8	0.3	0.1	2.7	0.8	Lysá hora Mt.	8.5	Stříbro	0.9
DJF	8.9	45.7	34.2	8.3	2.0	0.6	0.3	3.0	0.9	Lysá hora Mt.	10.2	Stříbro	1.0
MAM	9.6	52.4	32.2	4.7	0.8	0.2	0.1	2.8	0.7	Lysá hora Mt.	7.9	Stříbro	1.0
JJA	32.7	56.2	9.8	1.1	0.2	0.0	0.0	2.3	0.6	Milešovka	6.8	Vyšší Brod	0.8
SON	21.8	51.8	20.7	4.0	1.0	0.4	0.3	2.6	0.8	Lysá hora Mt.	9.3	Stříbro	0.8

and Stříbro (412 m a.s.l., no. 97 in Fig. 1) are the most frequently occurring stations with the absolute highest and lowest MDWSs, respectively (except JJA).

4.2. Temporal variability

Fluctuations in anomalies of seasonal and annual MDWSs (with respect to the 1961–1990 reference period) for 4 altitudinal groups and the entire Czech Republic (Fig. 6) show quite mild variations around the lines of linear trends rather than any well-pronounced intervals of higher and lower wind speeds. Such relatively uniform behaviour is confirmed by decreasing trends, which are all statistically significant (α = 0.05) (Table 2). Decreasing trends in absolute values are at their lowest in group I and highest in group IV for DJF, JJA and annual series. In seasonal distribution, the decrease is most pronounced in DJF for groups II–IV (SON in group I) and the entire Czech Republic, and weakest in JJA (MAM in group IV). Negative linear trends in monthly values were non-significant for January, July, September and December in the Czech Republic series, and always for 4 months in groups I and II and for 5 months in groups III and IV (Table 2). All altitudinal groups and the Czech Republic series show the highest decrease of MDWSs in November, except for group IV (February).

Since working up the linear trends for 4 altitudinal intervals and the entire Czech Republic provides an averaged series signal, linear trends for the 119 individual meteorological stations analysed were studied separately to reveal their variability in temporal (Fig. 7) as well as spatial (Fig. 8; Fig. S2 in the Supplement at www.int-res.com/articles/suppl/c072p197_supp.pdf) contexts. Despite a negative median of linear trends in all monthly, seasonal and annual MDWS trends (Fig. 7a), there exists a proportion of stations with positive trends (Fig. 7b). Slightly more than a third of all stations exhibited positive trends in January, July and September, and was statistically significant for 17 stations in May. In contrast, only 10 stations recorded positive trends in November, significant for only 3 stations (not any significant positive trend in February). November occupied quite a dominant position,

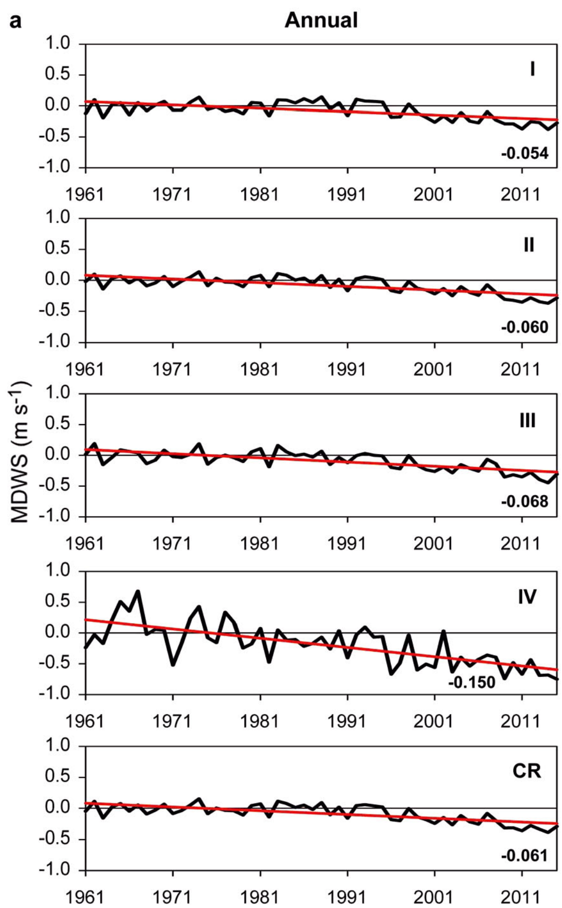

Fig. 6. Fluctuations in mean daily wind speed (MDWS) anomalies (with respect to 1961–1990 reference period) in 4 altitudinal groups (I: ≤300 m, II: 301–600 m, III: 601–900 m, IV: >900 m a.s.l.) and over entire territory of Czech Republic (CR) in 1961–2015 period for (a) annual and (b; next page) seasonal values. Red lines: linear trends (values in lower right in m s^{-1} decade^{-1}; all trends statistically significant, α = 0.05)

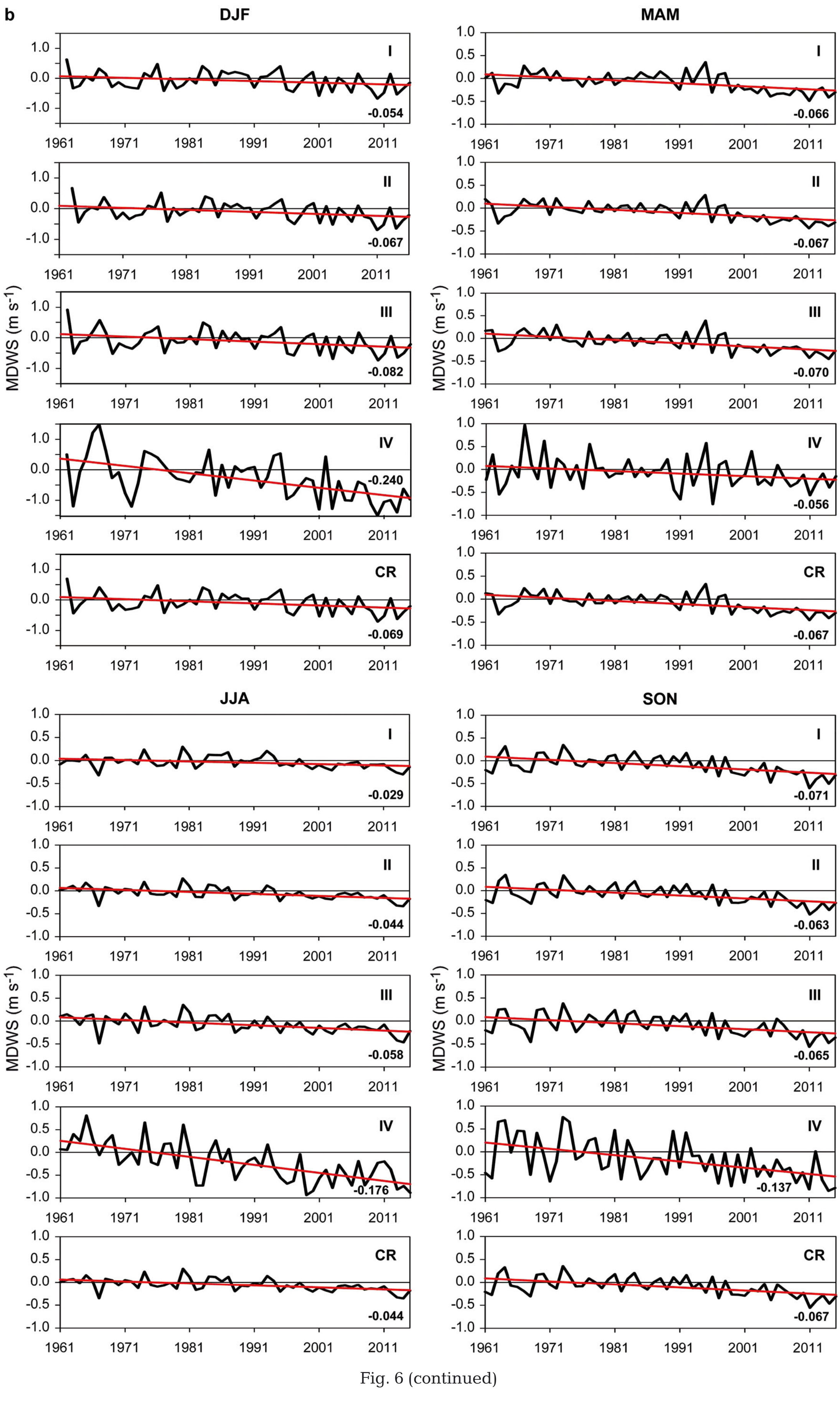

Fig. 6 (continued)

Table 2. Linear trends (m s^{-1} decade^{-1}) in monthly, seasonal and annual series of mean daily wind speeds for 4 altitudinal groups (I: ≤300 m, II: 301–600 m, III: 601–900 m, IV: >900 m a.s.l.) and the entire Czech Republic (CR) in the 1961–2015 period. **Bold**: statistically significant (t-test, α = 0.05)

Group of stations	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
I	–0.027	**–0.079**	**–0.073**	**–0.089**	**–0.034**	–0.026	–0.016	**–0.045**	**–0.051**	–0.046	**–0.115**	**–0.045**
II	–0.047	**–0.093**	**–0.062**	**–0.075**	**–0.063**	**–0.060**	–0.026	**–0.045**	–0.036	**–0.050**	**–0.104**	–0.057
III	–0.048	**–0.101**	**–0.072**	**–0.084**	**–0.053**	–0.083	–0.044	**–0.047**	–0.035	–0.049	**–0.112**	**–0.089**
IV	0.121	**–0.435**	**0.102**	**–0.346**	**0.075**	–0.227	0.048	**–0.349**	0.017	**–0.372**	–0.056	**–0.381**
CR	–0.039	**–0.096**	**–0.064**	**–0.085**	**–0.051**	**–0.057**	–0.025	**–0.050**	–0.039	**–0.054**	**–0.108**	–0.064

Group of stations	DJF	MAM	JJA	SON	Annual
I	**–0.054**	**–0.066**	**–0.029**	**–0.071**	**–0.054**
II	**–0.067**	**–0.067**	**–0.044**	**–0.063**	**–0.060**
III	**–0.082**	**–0.070**	**–0.058**	**–0.065**	**–0.068**
IV	**–0.240**	**–0.056**	**–0.176**	**–0.137**	**–0.150**
CR	**–0.069**	**–0.067**	**–0.044**	**–0.067**	**–0.061**

with 109 stations with negative linear trends (Fig. 7c), of which 69 were statistically significant. This month was followed by April with 100 such stations, of which 74 had significant trends. There were 66 stations with statistically significant negative trends in June, while in August this figure was 65 stations. In terms of seasons, the highest number of stations with positive trends was 29 in JJA (10 stations with significant trends), and with negative trends, 101 in SON (74 stations with significant trends in MAM). The lowest number of stations with positive trends was recorded in SON (18), with only one of them significant, while with negative trends, the lowest numbers were 90 stations in JJA and 54 stations with significant trends in DJF, respectively.

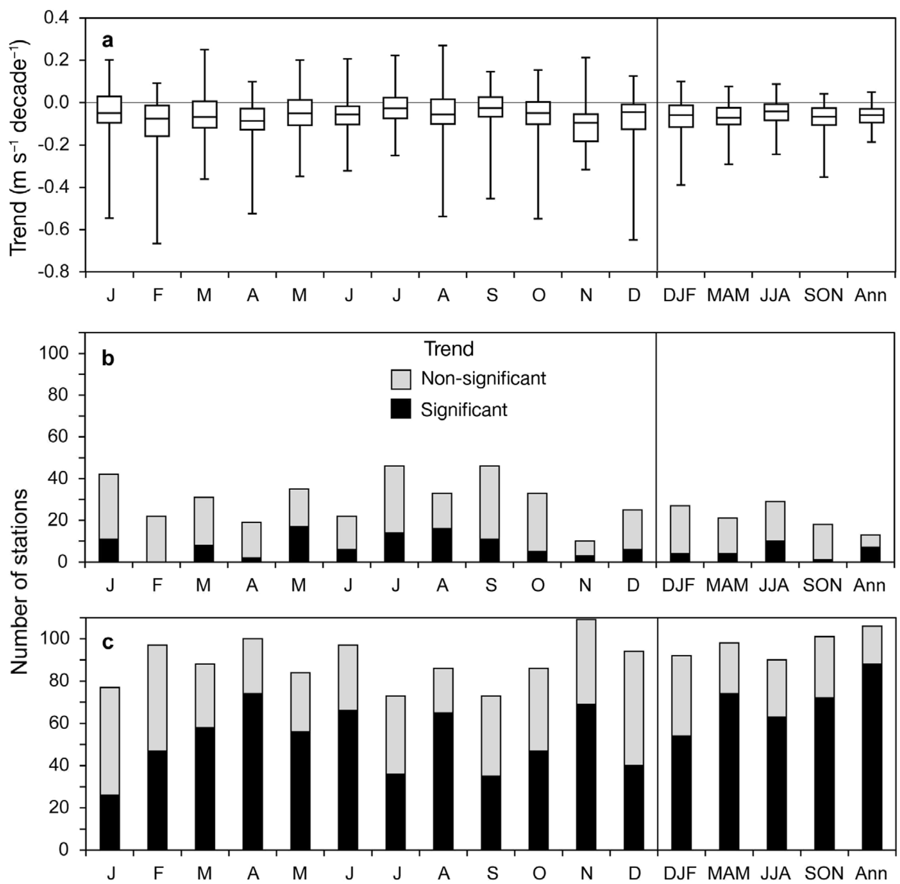

Fig. 7. (a) Linear trends in monthly, seasonal and annual series of mean daily wind speed at 119 meteorological stations over territory of Czech Republic in 1961–2015 period (box: median, lower and upper quartiles; whiskers: maximum and minimum). (b,c) Number of stations with positive and negative trends, respectively (statistical significance, α = 0.05)

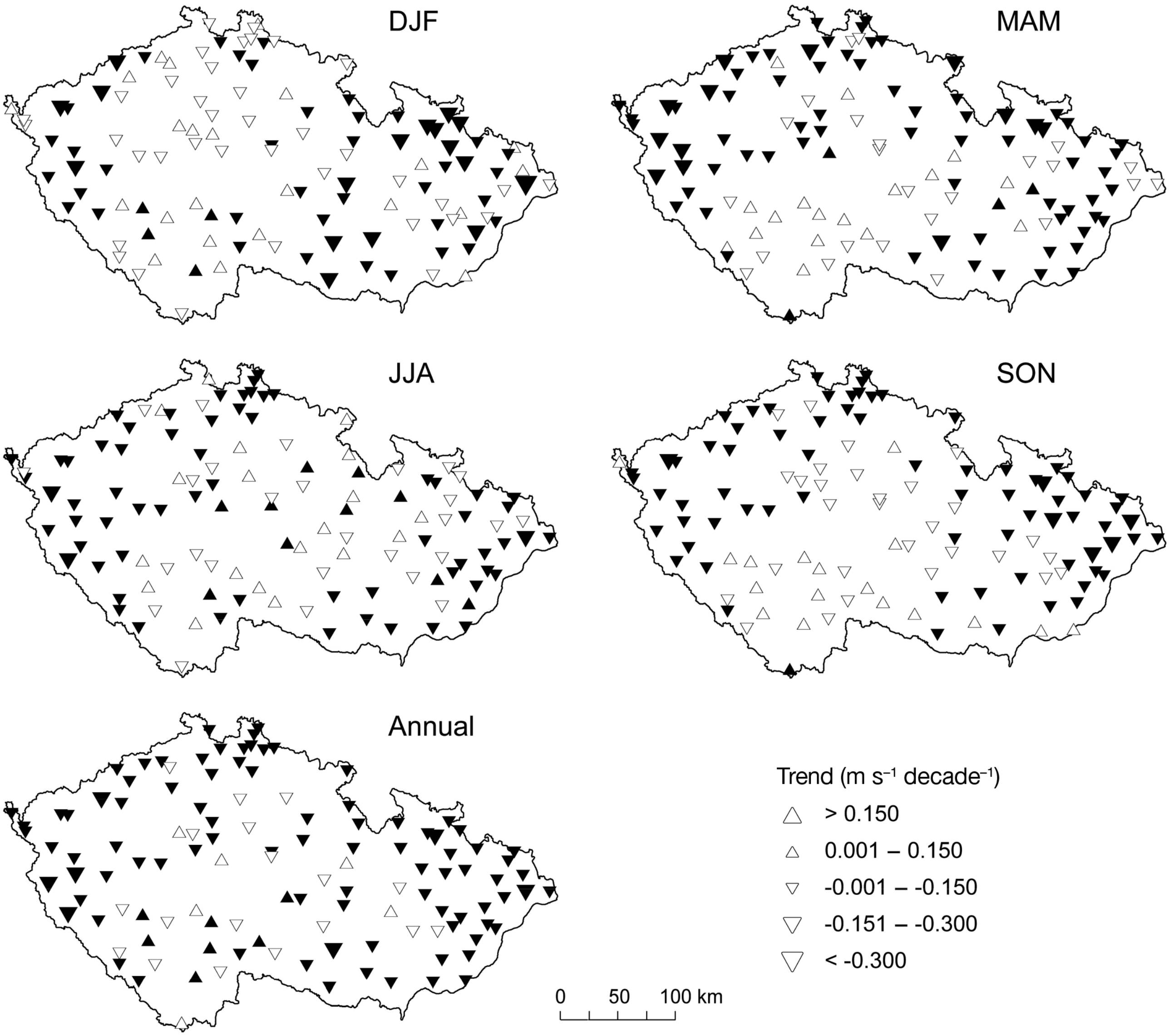

Fig. 8. Spatial distribution of sign, magnitude and statistical significance (α = 0.05) of linear trends in seasonal and annual mean daily wind speed series at 119 meteorological stations over territory of Czech Republic in 1961–2015 period (significant trends: solid symbols; non-significant trends: empty symbols)

The spatial distribution of the sign, magnitude and statistical significance of the linear trends is shown for monthly (Fig. S2 in the Supplement) and seasonal and annual (Fig. 8) MDWS series at the 119 meteorological stations over the territory of the Czech Republic in the 1961–2015 period. In view of the high spatial heterogeneity of wind speed fields, stations with opposite linear trends (positive vs. negative) may appear at relatively short inter-station distances. However, the dominant position of negative linear trends is well-expressed in the spatial structure of all months, seasons and the year, particularly in November and April. The share of positive trends increases notably in July and September, followed by January. In terms of seasons and the year, a slightly higher number of stations with positive trends occurs in JJA and DJF.

4.3. Wind speeds and atmospheric circulation

Because the North Atlantic Oscillation (NAO) is considered the most important circulation mode in Europe (compare e.g. Wanner et al. 2001, Trigo et al. 2002, Hurrell et al. 2003), NAOI series were correlated with monthly, seasonal and annual MDWS series from the 119 meteorological stations in the Czech Republic (Fig. 9a,b). The highest positive correlation coefficients in annual variation are achieved from December to March, something also confirmed by the highest number of stations with positive correlations, including those statistically significant (particularly January). Higher positive correlations prevailed in June as well, while the opposite held for April–May and July–November. As expected, among the seasons, this pattern applies for DJF (statistically significant except group IV), but relatively higher positive correlation coefficients also occurred in SON and annual series (Table 3a). Positive correlations in DJF were found for 114 stations (statistically significant for 78 stations; Table 3b).

However, it has been demonstrated (Brázdil et al. 2009) that, in searching for relationships between atmospheric circulation and climatic variables in the Czech Republic, better agreement may be achieved with changes in CEZI (Jacobeit et al. 2001). This has been applied here in the same way as NAOI (Fig. 9c,d, Table 3). The interval of highest positive correlation coefficients in this case includes the months from November to March and July, while negative correlation coefficients appeared for only May and September. Similar features also follow from the numbers of positive and negative correlation coefficients; a clear prevalence of negative correlations occurs only in May (Fig. 9d). The lowest, and non-significant, correlations were recorded in MAM, except group IV (Table 3a). Statistically significant positive correlation coefficients were recorded in DJF, SON (except group IV) and also JJA (except groups III and IV). Positive correlation coefficients achieved in DJF for 111 stations were statistically significant for 82 of them (Table 3b).

Comparing correlation coefficients obtained for monthly, seasonal and annual MDWSs with NAOI and CEZI (Fig. 9, Table 3), apparently closer relationships of wind speeds emerge with CEZI than NAOI. Higher correlations with NAOI were obtained only for April, May and October in group I; for May, June, August–October and annually in group II; for June, August, October and annually in group III; for May, June, August, October and annually in group IV; and May, June, August–October and annually for the entire Czech Republic. There were frequent cases in which negative correlation coefficients with NAOI were replaced by positives with CEZI. Moreover, statistically significant correlations with CEZI clearly predominate over those with NAOI.

Monthly, seasonal and annual linear trends of NAOI and CEZI for the 1961–2015 period were calculated for comparison with trends in MDWSs for the Czech Republic (Table 4). Decreasing trends for all 3 series were detected from July to October and in JJA and SON. Additionally, negative trends in May and annual NAOI series agreed with a declining tendency in MDWS values, while for CEZI this occurred only in November. Statistically significant decreases in NAOI series were detected in June, September, JJA and SON, and in CEZI series only in September (Table 4).

Table 3. Relationships of seasonal and annual mean daily wind speed series of 119 meteorological stations over territory of Czech Republic to atmospheric circulation expressed by North Atlantic Oscillation Index (NAOI) and Central European Zonal Index (CEZI) in the 1961–2015 period: (a) correlation coefficients for 4 altitudinal groups (I: ≤300 m, II: 301–600 m, III: 601–900 m, IV: >900 m a.s.l.) and entire Czech Republic (CR) (**bold**: significant values, α = 0.05); (b) total number of stations with positive or negative correlation coefficients

(a) Group of stations	NAOI DJF	NAOI MAM	NAOI JJA	NAOI SON	NAOI Annual	CEZI DJF	CEZI MAM	CEZI JJA	CEZI SON	CEZI Annual
I	**0.531**	–0.046	0.103	0.185	0.219	**0.581**	0.086	**0.311**	**0.345**	0.227
II	**0.484**	0.015	0.108	0.232	0.231	**0.526**	0.146	**0.284**	**0.368**	0.198
III	**0.495**	0.016	0.073	0.209	0.164	**0.526**	0.158	0.251	**0.401**	0.160
IV	0.266	0.076	0.120	0.173	0.146	**0.320**	**0.337**	0.200	0.248	0.070
CR	**0.502**	–0.001	0.104	0.216	0.218	**0.545**	0.139	**0.292**	**0.370**	0.199

(b) No. of stations	NAOI DJF	NAOI MAM	NAOI JJA	NAOI SON	NAOI Annual	CEZI DJF	CEZI MAM	CEZI JJA	CEZI SON	CEZI Annual
Positive	114	63	81	98	105	111	81	101	102	91
Significant positive	78	0	7	13	17	82	21	33	59	33
Negative	5	56	38	21	14	8	38	18	17	28
Significant negative	0	3	2	1	1	0	3	1	2	0

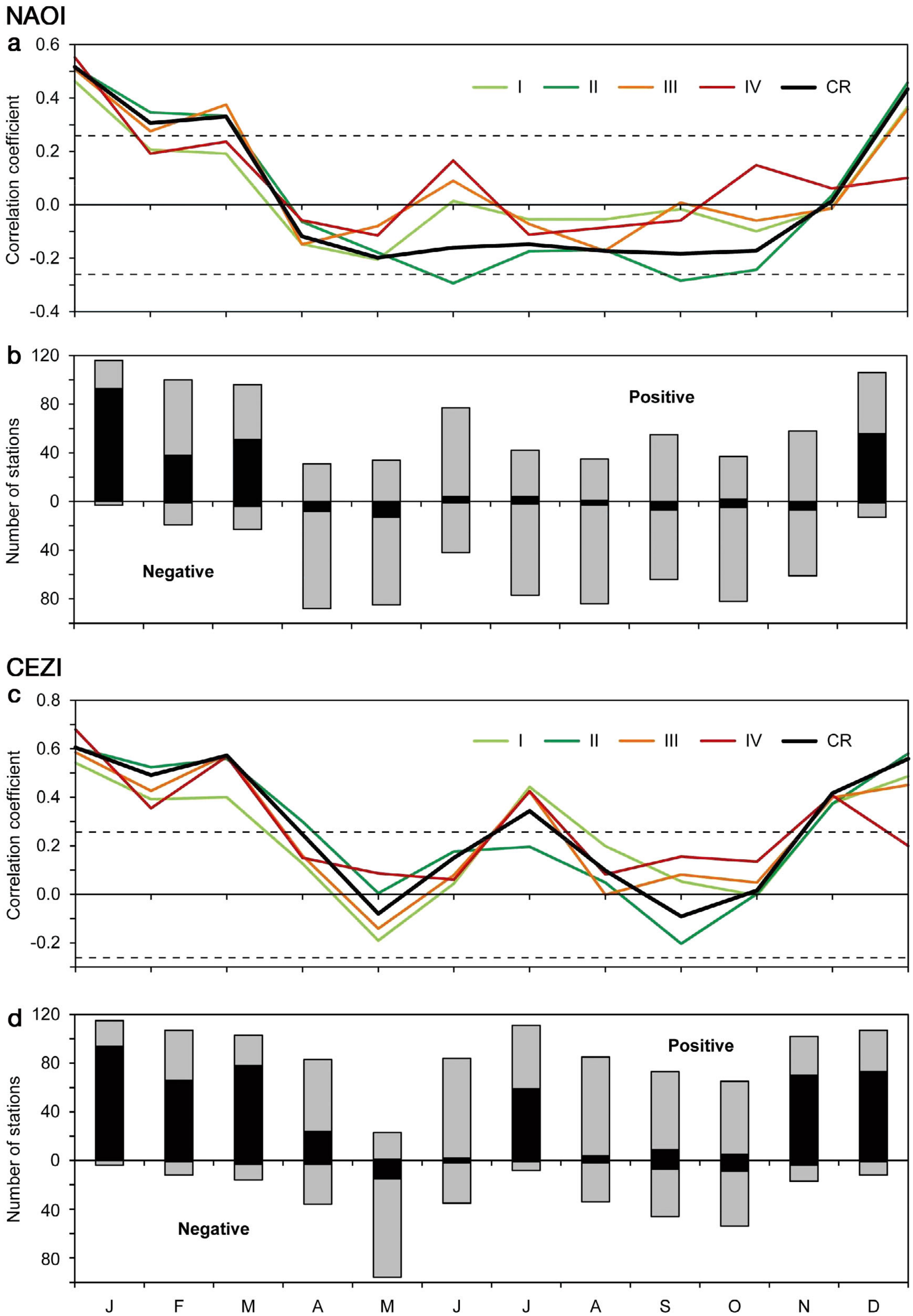

Fig. 9. Relationships of monthly mean daily wind speed series of 119 meteorological stations over territory of Czech Republic to atmospheric circulation expressed by (a,b) North Atlantic Oscillation Index (NAOI) and (c,d) Central European Zonal Index (CEZI) in 1961–2015 period: (a,c) correlation coefficients with levels of significance (α = 0.05; dashed lines) for 4 altitudinal groups (I: ≤300 m, II: 301–600 m, III: 601–900 m, IV: >900 m a.s.l.) and entire Czech Republic (CR); (b,d) total number of stations with positive or negative correlation coefficients (significant: black columns)

Table 4. Linear trends (m s^{-1} $decade^{-1}$) in monthly, seasonal and annual series of North Atlantic Oscillation Index (NAOI), Central European Zonal Index (CEZI) and mean daily wind speeds for Czech Republic (CR) in 1961–2015 period. **Bold**: statistically significant (t-test, $\alpha = 0.05$)

Index or CR	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
NAOI	0.162	0.201	0.015	0.050	−0.058	**−0.342**	−0.136	−0.082	**−0.317**	−0.255	0.057	0.243
CEZI	0.229	0.226	0.086	0.125	0.157	0.082	−0.120	−0.020	**−0.298**	−0.015	−0.036	0.256
CR	−0.039	**−0.096**	**−0.064**	**−0.085**	**−0.051**	**−0.057**	−0.025	**−0.050**	−0.039	**−0.054**	**−0.108**	−0.064

Index or CR	DJF	MAM	JJA	SON	Annual
NAOI	0.215	0.002	**−0.187**	**−0.172**	−0.038
CEZI	0.231	0.123	−0.019	−0.116	0.056
CR	**−0.069**	**−0.067**	**−0.044**	**−0.067**	**−0.061**

5. DISCUSSION

5.1. Wind speed measurements

The quality of wind speed measurements may be significantly influenced by the instruments used, their position and changes in station surroundings. At the CHMI, this is evaluated on the basis of a study by Sobíšek (1992). His assessment was prepared in the light of measurements taken with Metra anemographs and other types of anemometers for 197 stations over the territory of the Czech Republic. Sobíšek's methodology is also used for the routine quality control in the CLIDATA database application kept by CHMI, both for modern and historical wind speed data, since the year 2000. However, the 1990s saw the start of CHMI network automation of meteorological measurements, in the case of wind, by replacement of standard instruments with Vaisala wind sets and after 2000 by ultrasonic sensors (cf. Řepka 2011). Fig. 10 shows the increasing number of stations with automatic measurements between 1993 and 2015 among the total of 119 stations used in this study. The increase in the numbers of those stations coincides with an observed negative trend in annual MDWSs over the Czech Republic. This raises the question as to how much this artificial effect may have contributed to the observed decline.

Parallel wind speed measurements provided by a number of CHMI stations may be employed to estimate the possible influence of instrument changes on MDWS trends. Two examples are presented here (Figs. 11 & 12): for the Doksany (158 m a.s.l.; no. 22 in Fig. 1) and Kocelovice (519 m a.s.l.; no. 44 in Fig. 1) stations with measurements in the 2000–2015 period (changes in measurements by automatic wind speed sensors at both stations appear in Fig. 12). Fig. 11 shows histograms of the relative differences in seasonal and annual MDWSs in standard (anemograph) and automatic measurements. Because the 3 daily wind speed readings are archived as integers, differences in daily means are expressed as values of 0.0, ±0.3, ±0.7, ±1.0 m s^{-1}, etc. Results for the Doksany station (Fig. 11) show agreements in the measurements of the 2 instru-

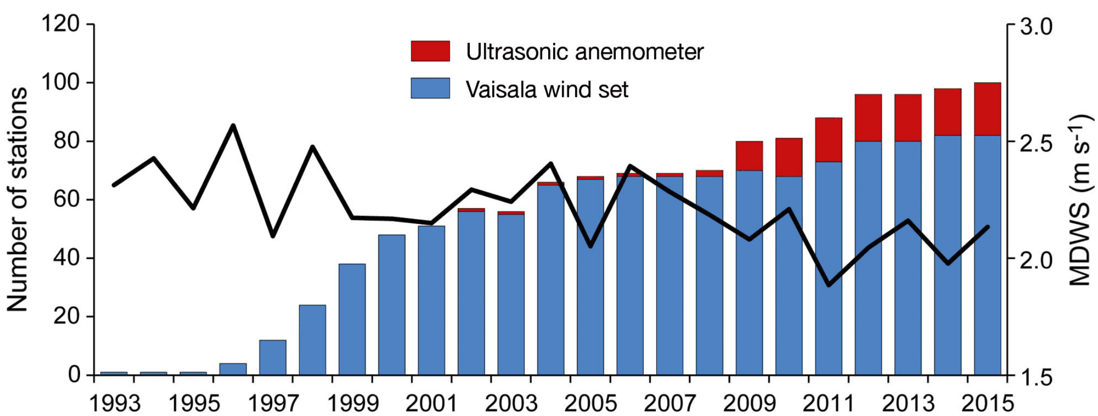

Fig. 10. Number of stations used in this study measuring wind speeds (bars) by Vaisala wind set and ultrasonic anemometer in comparison with fluctuations in annual mean daily wind speed (MDWS, black line) over territory of Czech Republic in 1993–2015

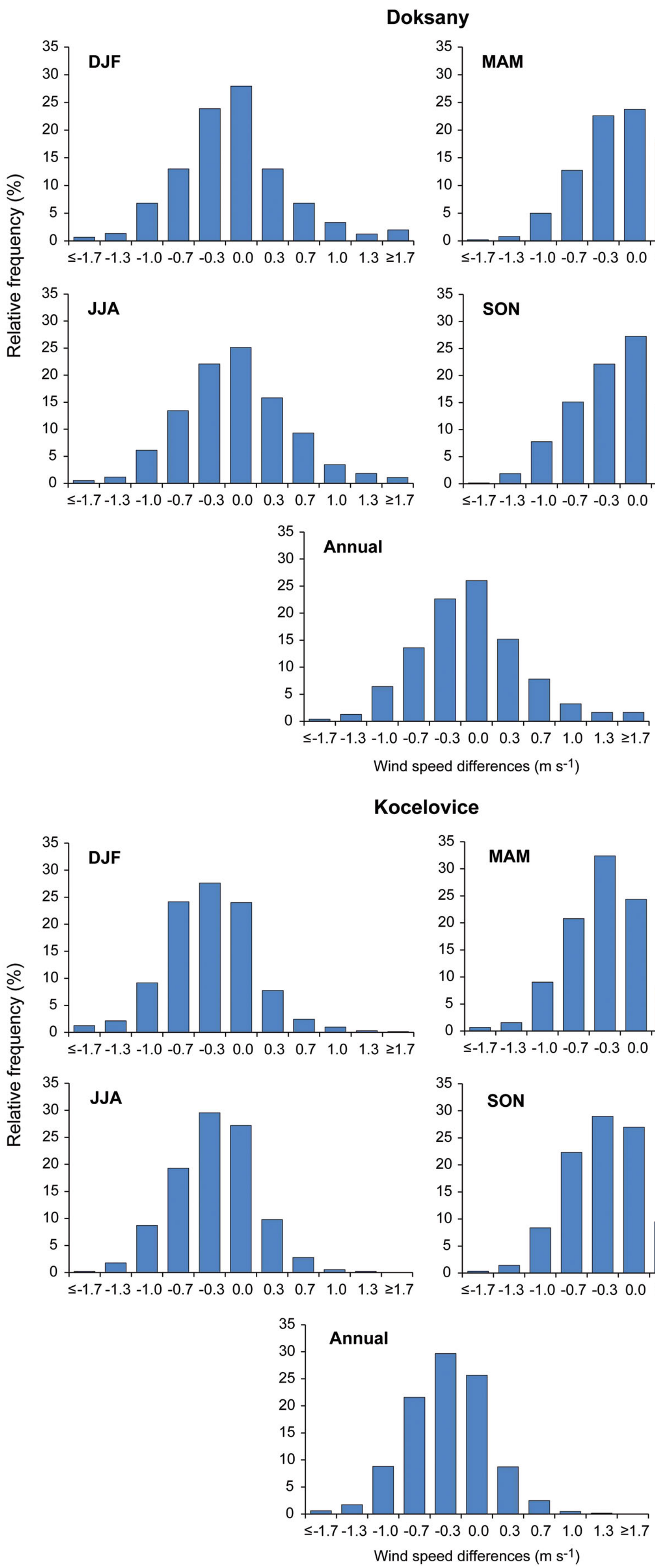

Fig. 11. Relative frequencies of differences in seasonal and annual mean daily wind speeds according to standard and automatic measurements at Doksany and Kocelovice stations in 2000–2015

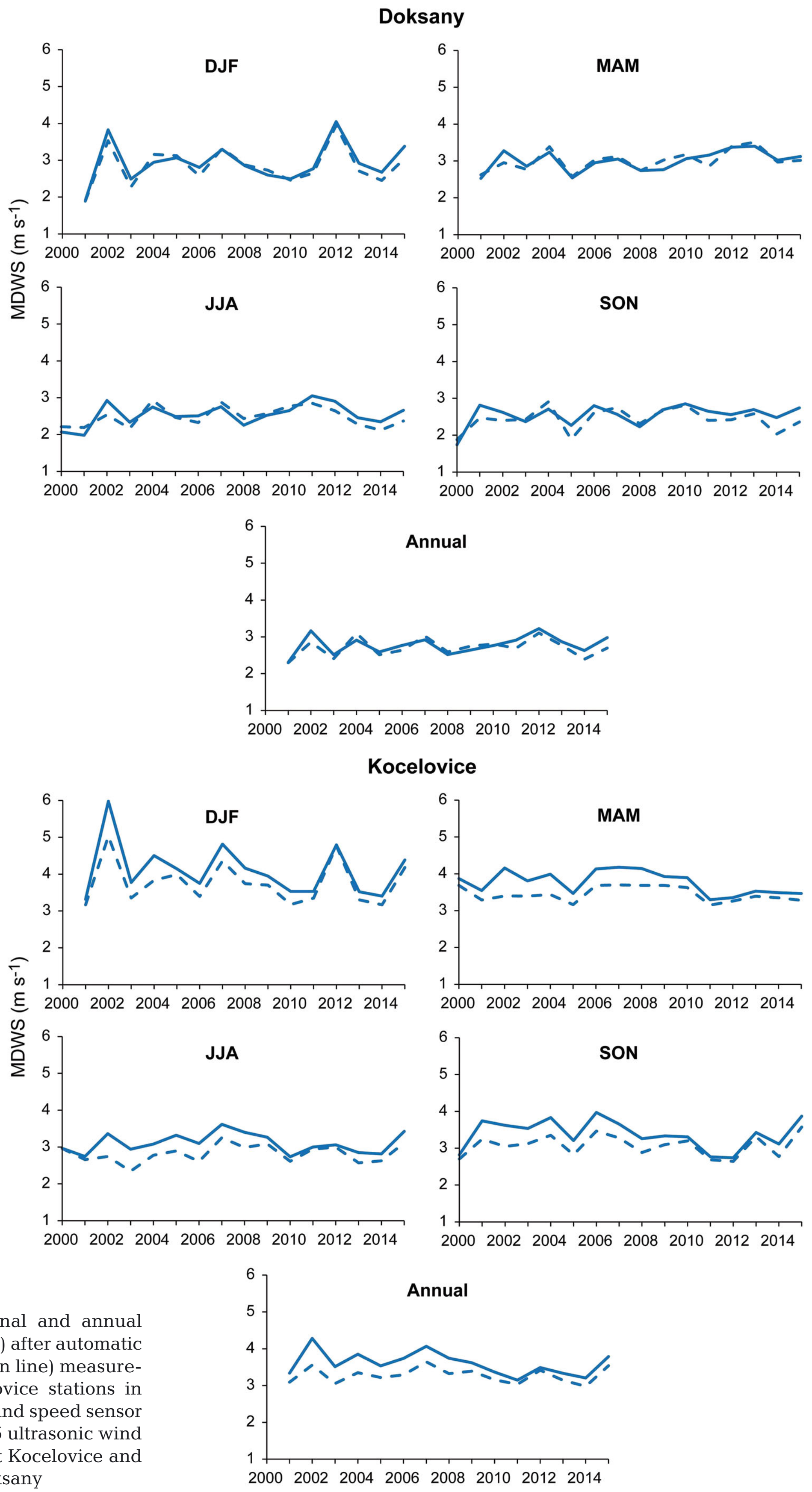

Fig. 12. Fluctuations in seasonal and annual mean daily wind speed (MDWS) after automatic (solid line) and standard (broken line) measurements at Doksany and Kocelovice stations in 2000–2015. Vaisala WAA251 wind speed sensor was replaced by Vaisala WS425 ultrasonic wind sensor on 15 November 2011 at Kocelovice and 12 April 2012 at Doksany

ments of between 23.8% (MAM) and 27.9% (DJF) on corresponding days, but negative differences of -0.3 m s^{-1} appear (i.e. MDWSs measured by anemograph are lower compared to automatic measurements) more frequently than positive differences at $+0.3$ m s^{-1} (the same situation also holds for differences with values of ± 0.7 and ± 1.0 m s^{-1}). However, in MDWS fluctuations during the 2000–2015 period, there are some years (e.g. in MAM or JJA) in which standard measurement gave higher values (Fig. 12). In contrast, the Kocelovice station shows consistently lower seasonal and annual MDWSs measured by anemograph over the entire 2000–2015 period (Fig. 12). This clearly follows from histograms of the corresponding differences in Fig. 11: despite zero differences (agreement in both measurements) occurring on between 24.0% (DJF) and 27.2% (JJA) of days, the negative differences achieving -0.3 m s^{-1} clearly prevail over those of $+0.3$ m s^{-1}, and are the most frequent for all seasons, as well as the year (between 27.6% in DJF and 32.4% in MAM). A similar predominance of negative differences above positive is clearly apparent (Fig. 11). These results may be related to the significantly higher starting wind speed threshold and overspeeding problems associated with standard cup anemometers compared to low-threshold anemometers (Vaisala wind set) or ultrasonic wind sensors (see e.g. Brock & Richardson 2001). Further measurement uncertainty may follow from the rounding out of actual daily wind speed readings to integers, the only form in which they are available in the CHMI database.

Although any far-reaching conclusions from such limited analyses must be addressed with great care, it seems that negative wind speed trends (including 'wind stilling') — explained by changes in atmospheric circulation and increased surface roughness, as reported by Vautard et al. (2010), or increased roughness length together with other forcings, as reported by Bichet at al. (2012) and Wever (2012) — cannot be clearly attributed to the effects of the automation of wind speed measurements. These points raise interesting challenges for further research in this field. The results obtained by Azorin-Molina et al. (2017), who studied trends in daily wind speeds for selected Spanish stations during the 1961–2011 period, based on various numbers of daily readings, appear to tally with this. They found stronger negative trends for annual and seasonal series of daily wind speeds calculated for 4 synoptic terms compared to those calculated from 24 h wind run measurements. The percentage of stations showing wind stilling in the first case (63.2%) was much higher than in the second (36.8%).

5.2. Comparison of linear trends

Based on the results presented in Section 4.2, a long-term, statistically significant decrease in wind speeds is a typical feature of MDWS variability for the 119 meteorological stations over the territory of the Czech Republic during the 1961–2015 period. This is uniformly expressed in mean monthly, seasonal and annual series calculated for 4 altitudinal intervals and the entire Czech Republic (Table 2, Fig. 6). Statistically significant seasonal negative trends for the Czech Republic fluctuate between -0.069 m s^{-1} decade^{-1} for DJF and -0.044 m s^{-1} decade^{-1} for JJA, with an annual decline of -0.061 m s^{-1} decade^{-1}. Some negative trends were previously indicated in monthly, seasonal and annual wind speeds for 22 Czech homogenised climatological stations in the 1961–2005 period (Brázdil et al. 2009), as well as in extension of the same data to the 1961–2014 period (Brázdil et al. 2017). Moreover, a similar declining tendency has also appeared in series of maximum daily wind gusts analysed for 19 Czech synoptic stations in the latter period (Brázdil et al. 2017).

Moving to the European scale, several studies for other regions present similar results. A decrease in storminess of between 5 and 10% per decade in the 1962–2002 period at Dutch meteorological stations emerged from the work of Smits et al. (2005), who analysed moderate wind events (occurring 10 times a year on average) and strong wind events (occurring twice a year on average). Péliné Németh et al. (2011) reported generally decreasing tendencies in mean wind speeds and gusts for 36 Hungarian synoptic stations in the 1997–2010 period. A downward wind-speed trend of -0.016 m s^{-1} decade^{-1} was recorded by Azorin-Molina et al. (2014) in their analysis of a homogenised series of 67 stations covering Spain and Portugal in 1961–2011. Romani et al. (2015) described negative trends in the Koshava wind (with wind speeds >5 m s^{-1}), blowing from the southeast quadrant over Serbia, Bulgaria and Romania, during the 1949–2010 period. Azorin-Molina et al. (2016) reported daily peak wind gusts for 80 Spanish and Portuguese stations in 1961–2014, and found slight negative annual trends (-0.005 m s^{-1} decade^{-1}) with seasonal differences (DJF: -0.168 m s^{-1} decade^{-1} at $p < 0.10$, JJA: 0.130 m s^{-1} decade^{-1} at $p < 0.05$).

McVicar et al. (2012) used 148 studies worldwide to investigate wind stilling on a larger scale and reported a wind speed decline of -0.140 m s^{-1} decade^{-1}, based on studies with >30 sites and observations covering >30 yr. Papers quoted in their overview may be supplemented by several published later. For example, for Asia, Xiaomei et al. (2012) reported a statistically significant annual wind speed trend of −0.24 m s^{-1} $decade^{-1}$ for 110 stations in southwestern China during the 1969–2009 period. Chen et al. (2013) found pronounced downward trends in annual mean wind speeds for 540 stations in China in the 1971–2007 period. Dadaser-Celik & Cengiz (2014) reported downward trends in annual wind speeds for 62% of 206 stations analysed in Turkey for the 1975–2006 period, with a value of −0.14 m s^{-1} $decade^{-1}$. A decreasing wind-speed trend in South Korea was observed from the mid-1950s until 2003, but became unclear thereafter (Kim & Paik 2015). Shi et al. (2016) found a significant decrease in wind speed at the majority of the 179 stations situated in a desertification-prone region of China in 1960–2013. Guo et al. (2017) reported decreases in wind speeds in all seasons (particularly in MAM) and annually for 139 stations on the Tibetan Plateau in the 1970–2012 period, with greater changes at higher elevations.

In terms of the ways in which MDWS trends may be related to atmospheric circulation changes, the generally prevailing west and northwest winds over the territory of the Czech Republic (cf. Sobíšek 2000, Tolasz et al. 2007) make evident the influence of NAOI and CEZI, 2 important circulation modes. For example, Donat et al. (2010) demonstrated that 80% of windstorm days in central Europe are related to western flow, corresponding to a positive NAO phase. This is confirmed by established positive correlations of MDWS series with both circulation characteristics, particularly during the months of the winter half-year, when basic circulation modes are especially apparent. Weakening of macro-scale circulation patterns, or their disruption by meso-scale phenomena (e.g. convection) during the summer half-year contribute to weakening of interrelationships of MDWSs to both indices; they may even become negative. These factors affect important seasonal changes in the climatic effects of NAOI, as many authors report from studies analysing various climatic variables (e.g. Trigo et al. 2002, Jones et al. 2003, Beranová & Huth 2007, Brázdil et al. 2009, 2017, Azorin-Molina et al. 2014). Moreover, as Pokorná & Huth (2015) note in their investigation of temperature and precipitation patterns and NAO in Europe, effects and consequences are sensitive to how NAO is defined. Finally, higher correlations of MDWSs with CEZI than with NAOI result from the closer territorial focus of CEZI with respect to the central European area, and confirm previous results from other contributors (e.g. Brázdil et al. 2009).

A number of studies have attempted to explain the wind-stilling effect. Vautard et al. (2010), who found a wind speed decrease of 5–15% for 822 stations in the northern mid-latitudes during the 1979–2008 period, attributed it to atmospheric circulation (10–50%) and increased surface roughness (25–60%). Bichet et al. (2012) explained a wind speed decline of −0.3 m s^{-1} over the past 30 yr in northern land mid-latitudes in terms of increased roughness, together with other forcings over the longer term (atmospheric aerosols, SST and greenhouse gas concentrations). Wever (2012), using 20 Dutch stations, mentioned a doubling of the local roughness length between 1962 and 2009, which was particularly apparent after 1981, with a decrease in wind speed of −0.13 m s^{-1} $decade^{-1}$. He attributed 70% of the wind speed trend to surface roughness. Romani et al. (2015) explained the weakening of the Koshava wind only meteorologically, citing changes in synoptic circulation and temperature, together with a weakening of the Siberian High and the west-Mediterranean cyclones. In connection with the decrease in maximum wind gusts over the Czech Republic, Brázdil et al. (2017) referred to changes in land use, characterised in particular by a considerable decrease in arable areas and a steady increase in forest, and in built-up and other non-agricultural areas. An example of such changes in the Czech Republic may be found in the surroundings of the Přimda station in the Český les Highlands (743 m a.s.l.; no. 87 in Fig. 1), where a considerable increase in the forested area around the station between 1958 and 2008 (Fig. 13) has taken place. A similar situation, affecting the Červená station in the Oderské vrchy Highlands (749 m a.s.l.; no. 16 in Fig. 1), is reported in Řepka (2011).

6. CONCLUSIONS

This analysis of homogenised monthly, seasonal and annual MDWS series for 119 meteorological stations over the territory of the Czech Republic in the 1961–2015 period introduced new results, which may be summarised as follows:

(1) There exists great spatial variability in wind speed patterns. Despite the established rise in wind speed with altitude, increasing distance between stations is more important for decreasing correlations between them.

(2) Complicated spatial variability is also reflected in the different temporal variability expressed by

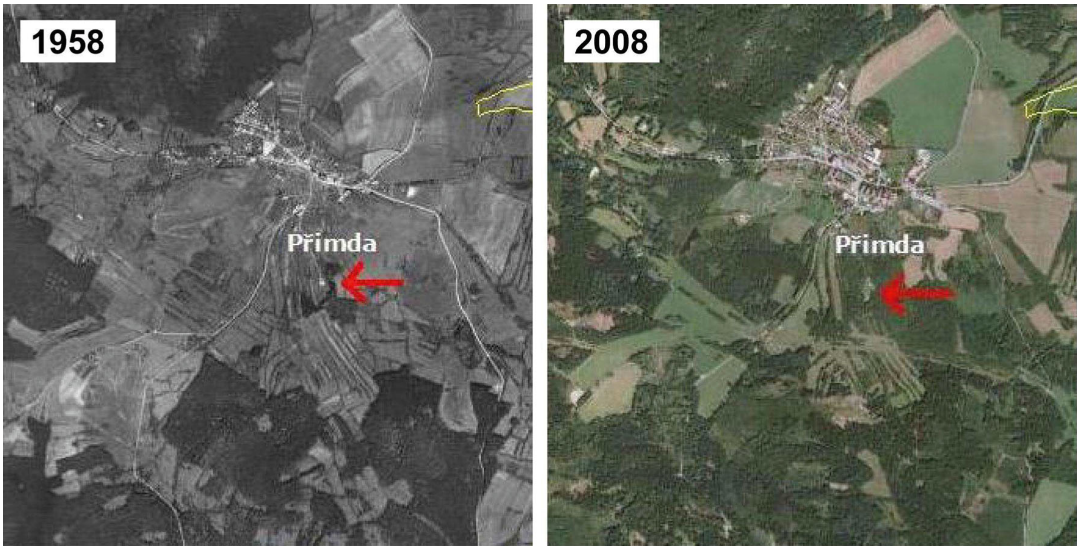

Fig. 13. Comparison of surroundings of the Přimda station in 1958 and 2008, showing increase in forested and built-up areas (archives of CHMI)

linear trends showing a broad variety of statistically significant or non-significant positive (increase in MDWSs) and negative (decrease in MDWSs) trends, which can be opposite even at relatively close stations. However, the fact that the majority of stations exhibit negative trends is reflected in a mean declining tendency in wind speed over the territory of the Czech Republic in all months and seasons, as well as annually, at its strongest particularly in November and April among months (–0.108 and –0.096 m s^{-1} decade^{-1}, respectively) and in DJF (–0.069 m s^{-1} decade^{-1}) among seasons (–0.061 m s^{-1} decade^{-1} in annual series).

(3) Winter half-year MDWS fluctuations are positively correlated with NAOI and CEZI as 2 important modes of atmospheric circulation on the central European scale. In general, CEZI shows better relationships than NAOI, extending highly positive and statistically significant correlations from November to March as well as in July.

(4) The negative trends in Czech MDWS series demonstrated here are in agreement with the well-known ‘wind stilling’ observed in many places worldwide, and well documented in many references. In response to explanations of this effect in terms of changes in atmospheric circulation, increasing surface roughness or other forcings, we recommend that the effects of changes in instruments, with widespread replacement of standard measurements with new, automatic wind-speed sensors in meteorological networks, be considered as an interesting direction for further research.

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