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Wind-stilling in the light of wind speed measurements: the Czech experience

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ABSTRACT: Changes of instruments often give rise to significant break-points in wind-speed series. This is particularly applicable when measurements are automated, a process that started in the Czech Republic in the mid-1990s, when standard universal anemographs were progressively replaced by the Vaisala WAA251 sensor (cup anemometer) and the WS425 sensor (ultrasonic). Parallel wind speed measurements, by universal anemographs and Vaisala sensors, at the Doksany (2000–2016) and Kocelovice (2000–2016) stations enabled differences in the 2 types of measurement to be analysed. Vaisala sensors measure, on average, higher wind-speeds than universal anemographs, particularly in calm situations and at low wind speeds. The differences between the 2 types of instrument do not depend on wind direction. Linear trends of homogenised daily mean wind-speed series from only a universal anemograph or combined from universal anemograph and Vaisala sensors generally exhibit no important differences in their significance or values. This could indicate that observed decreasing trends in mean daily wind-speeds (‘stilling’) cannot be attributed to changes of wind-speed measurements to automated devices; with respect to only 2 stations being investigated, this is biased by high uncertainty. In contrast, important differences in the 2 types of measurement, both in linear trends and their significance, appear for series of 3 daily readings (07:00, 14:00 and 21:00 h LMT).

KEY WORDS: Universal anemograph · Vaisala wind-speed sensors · Wind speed · Homogenisation · Wind stilling · Czech Republic

1. INTRODUCTION

Wind speeds and the strength of wind gusts have direct implications for society and its infrastructure. The occurrence of high winds, particularly windstorms, with all their associated consequences, including not only material damage but also loss of human life and other casualties (Ulbrich et al. 2013), is especially worthy of study. Knowledge of spatio-temporal wind speed/gust variability is an important tool if the negative impacts of such events are to be diminished.

In the study of temporal wind speed variability, a remarkable decrease in wind speeds during recent decades has emerged, for which Roderick et al. (2007) coined the term (wind) ‘stilling’. This decrease has been recorded in various wind speed series for the past 30–50 yr worldwide, particularly in land mid-latitudes; McVicar et al. (2012) provide an overview. From more recent papers, not reported in that study, stilling has been further demonstrated in Europe (e.g. Péliné Németh et al. 2011, Azorin-Molina et al. 2014, 2016, 2017, Romani et al. 2015, Minola et al. 2016, Brázdil et al. 2017a,b, Kohler et

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*Corresponding author: brazdil@sci.muni.cz al. 2017, Laapas & Venäläinen 2017) and in Asia (e.g. Guo et al. 2011, Xiaomei et al. 2012, Chen et al. 2013, Dadaser-Celik & Cengiz 2014, Kim & Paik 2015, Shi et al. 2016, Guo et al. 2017). Several papers have attempted to explain these negative trends, especially in terms of increasing land-surface roughness (Vautard et al. 2010, Bichet et al. 2012, Wever 2012), but also for other reasons (for overviews, see e.g. McVicar et al. 2012, Azorin-Molina et al. 2016). Decreasing trends derived from wind-speed measurements are underestimated by climate model simulations (Bichet et al. 2012) and may disagree with changes in storminess derived from calculations of geostrophic wind (Matulla et al. 2008) or re-analyses (e.g. McVicar et al. 2008, Brönnimann et al. 2012).

Homogenisation is key to the analysis of measured wind-speed series. While various tests of relative homogeneity may be employed for detection of break-points in wind-speed series (e.g. Alexandersson 1986, Štěpánek et al. 2011), the creation or disclosure of homogeneous reference series remains the main problem. Various approaches appear in the existing literature. For example, Wan et al. (2010) used monthly mean geostrophic wind-speed (geowind) series for homogenisation of 117 stations in Canada as reference series. Azorin-Molina et al. (2014, 2016), homogenising wind-speed/gust series for stations throughout the Iberian Peninsula, used simulations with the mesoscale model MM5 for that purpose. Brázdil et al. (2017b) homogenised wind-speed series from 119 meteorological stations in the Czech Republic in terms of pair-wise detection, always from the 5 best-correlated neighbouring stations. Laapas & Venäläinen (2017) used the HOMER homogenisation tool for monthly mean and maximum wind speed series from 144 Finnish stations, divided into 7 'geographically uniform networks'; each station was then compared with those in the same network.

Despite reported problems associated with instrument changes or changes in observing procedure during wind-speed measurements noted by the majority of papers, more detailed attention to these problems is often absent, with some notable exceptions (e.g. DeGaetano 1998, Wan et al. 2010, Thomas & Swail 2011, Azorin-Molina et al. 2016, Brázdil et al. 2017b). The reason for this might lie in a belief that such inconsistencies are removed during the homogenisation procedure on the one hand, or in missing series of long-term comparative measurements on the other.

The most recent important change in wind speed/gust measurements in the Czech Republic was related to the introduction of automatic instruments from the mid-1990s onwards (Řepka 2011). As Fig. 1 indicates, the most significant decrease in mean wind speeds coincides closely with the widespread introduction of automatic measurements, particularly after 2000. Brázdil et al. (2017b) came to a preliminary conclusion, based on simple analysis of comparative measurements at 2 stations, that the effect of automation should not play a key role in observed wind-stilling, and recommended further research for better understanding of this phenomenon.

Because it has in hand long-term parallel wind-speed measurements from 2 Czech stations, the present study is in a position to demonstrate whether, and in what ways, automatic wind speed measurements influence perceptions of the spatiotemporal variability of wind speeds compared with standard measurements.

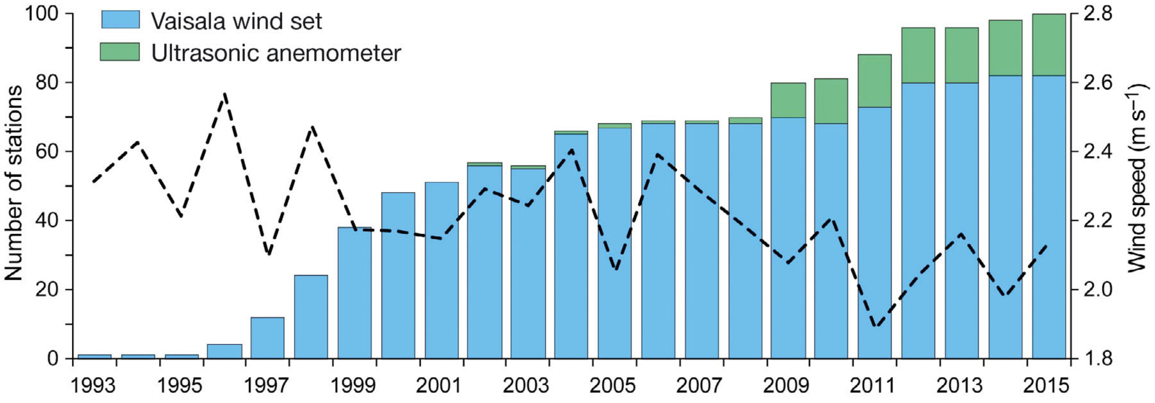

Fig. 1. Number of stations measuring wind speeds by Vaisala wind set and ultrasonic anemometer in comparison with fluctuations in annual mean daily wind speed (dashed line) over the territory of the Czech Republic in 1993–2015, calculated from homogenised series of 119 meteorological stations (adapted from Brázdil et al. 2017b)

2. DATA

The process of automation of meteorological measurements taken by the network of meteorological stations of the Czech Hydrometeorological Institute (CHMI) began around the mid-1990s. The change from standard manual to automatic measurements at any given station was quite sudden, not usually including a period of overlapping comparative measurements. Wind-speed measurements were no exception, when universal anemographs (anemo-indicators) were replaced by Vaisala WAA151 and WAA251 wind-speed sensors (cup anemometer), or later by Vaisala WS425 sensors (ultrasonic). The universal anemograph (of the Metra type) has a wind-speed range of between 0 and 40 m s^{-1}, with a sensitivity threshold of 1 m s^{-1} (measurement accuracy was not specified). The Vaisala cup anemometer measures wind speeds in the 0.4–75 m s^{-1} range, with a sensitivity threshold of <0.5 m s^{-1} (with optimal orientation of cups, even <0.35 m s^{-1}) and a measurement accuracy ±0.17 m s^{-1}. The ultrasonic sensor has a measurement range of 0–65 m s^{-1}, a sensitivity threshold of 0.1 m s^{-1} and measurement accuracy of ±0.135 m s^{-1} (Řepka 2011).

For only 2 stations of the CHMI, those at Doksany and Kocelovice, comparative wind speed measurements were organised, creating a database for subsequent statistical analysis. All their wind-speed instruments were regularly calibrated or exchanged in agreement with standard instructions of the CHMI for the maintenance of high-quality observations.

The Doksany station (φ = 50° 27′ 36″ N, λ = 14° 10′ 12″ E, H = 158 m a.s.l.) is located in the flat terrain of the Polabská nížina Lowlands, a typical countryside station. The universal anemograph was used from 8 October 1963, the Vaisala WAA251 sensor from 1 April 2000 and the WS425 sensor from 12 April 2012. Thus, comparative wind speed measurements are available from 1 April 2000 to 31 December 2016. The universal anemograph is located on a pole extending from the roof of the station building (Fig. 2a), while the Vaisala WS425 sensor is installed at a distance of 45 m on a separate pole (Fig. 2b), where the previous WAA251 wind sensor was also located. The instruments are located 10 m above the ground.

The Kocelovice station (φ = 49° 28′ 12″ N, λ = 13° 50′ 24″ E, H = 519 m a.s.l.) is located in the Středočeská pahorkatina Hilly Land, another typical countryside station. The universal anemograph was used from 1 March 1975, the Vaisala WAA251 sensor from 1 January 1996 and the WS425 sensor from 15 November 2011. However, comparative measurements are available from 1 January 2000 to 31 December 2016. All the wind instruments are located on poles extending from the roof of the station building: universal anemograph (Fig. 3a) and WAA251 and WS425 wind sensors (Fig. 3b). The distance between them is 9 m, and they are 10 m above the ground.

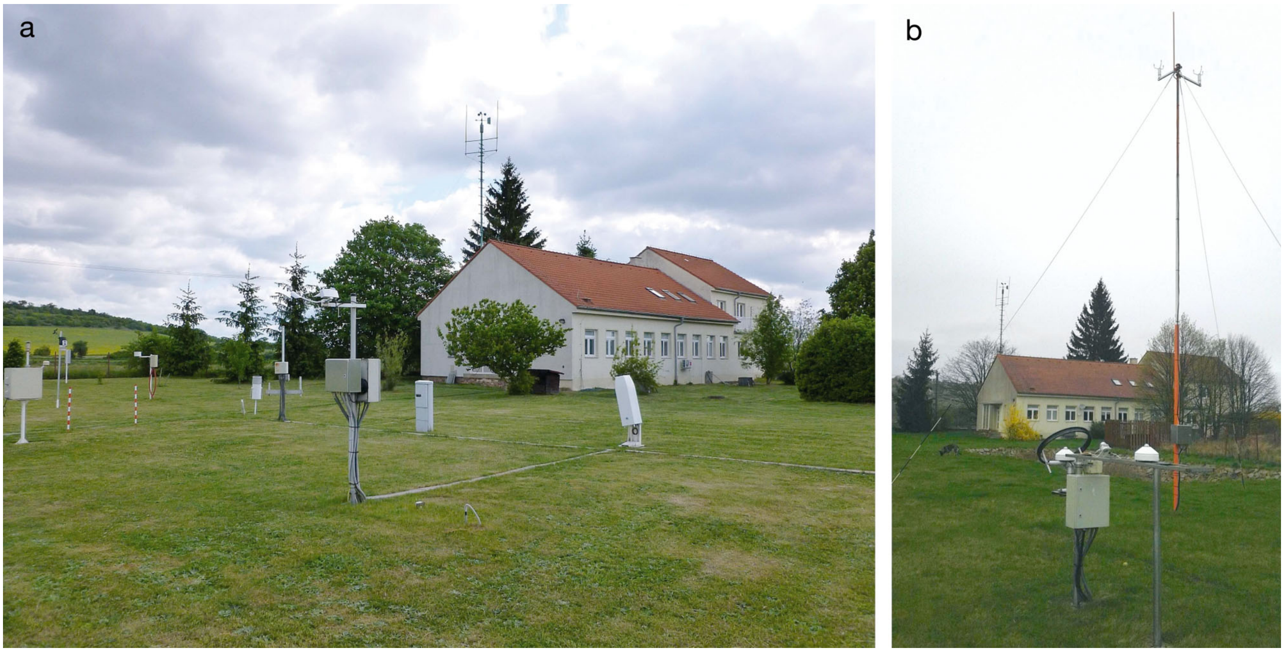

Fig. 2. The Doksany meteorological station: (a) building with universal anemograph; (b) WS425 wind sensor in the foreground (photo: Martin Možný)

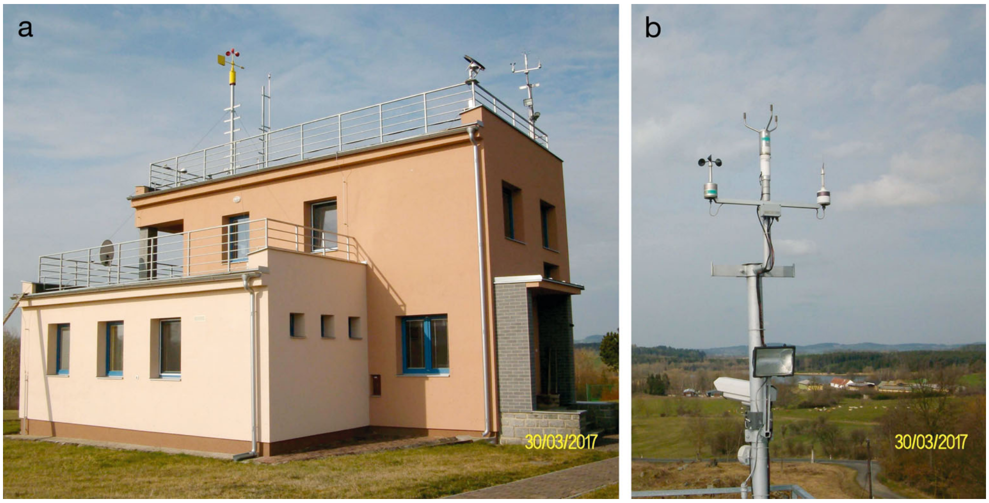

Fig. 3. The Kocelovice meteorological station: (a) position of universal anemograph and Vaisala wind sensors on the roof of the station building; (b) detailed view of Vaisala wind sensors: WAA251 (left) and WS425 (at the top) (photo: Jaroslav Stalmacher)

Data collected for the Doksany and Kocelovice stations include values for wind speed (rounded to integers in m s^{-1}) and wind direction (in tenths of degrees) for 3 daily readings at 07:00, 14:00 and 21:00 h LMT, from which daily mean wind speed was calculated as an average of the three daily readings. Data for the regular calibration of the wind-speed sensors and their changes exist in the metadata of both stations. The following abbreviations are further used for reporting individual types of wind-speed instrument: universal anemograph (UAG); Vaisala WAA251 cup anemometer (VCA); Vaisala WS425 ultrasonic sensor (VUS).

3. METHODS

The basic statistical analysis of wind speeds was performed separately for series of 3 daily readings at 07:00, 14:00 and 21:00 h LMT and for daily means. For each station, the periods of analysis were limited by the use of one particular type of automatic instrument for which data from UAG were also available. For example, analysis for the Doksany station concentrates on 2 periods: 1 April 2000–11 April 2012 (comparative measurements by UAG and VCA) and 12 April 2012–31 December 2016 (UAG and VUS). The results of basic statistical analysis are presented as box-plots (maximum and minimum values, 10th and 90th percentile, lower and upper quartile, median) (see Fig. 4) and average with standard deviation (see Table 2). The significance of differences expressed as averages calculated for a given pair of instruments was evaluated using *t*-test differences in the mean at a significance level $\alpha = 0.05$. Relative frequencies of individual wind speeds were also expressed as histograms (see Fig. 5) and fitted by the representative curve. If values of wind speeds were not expressed as full integer values (e.g. 0, 1, 2, ... m s^{-1}), a wind speed of 0 m s^{-1} is categorised with speeds up to 0.50 m s^{-1}, a wind speed of 1 m s^{-1} as in the 0.51–1.50 m s^{-1} interval, a wind speed of 2 m s^{-1} as speeds in the 1.51–2.50 m s^{-1} interval, etc. Mean wind speeds for individual wind directions are presented in the form of wind roses (see Fig. 6).

To show the possible effects of instrument changes on the homogeneity of wind-speed series and to derive their linear trends, 2 series were always created for each station. The first series was a combination of measurements from UAG and Vaisala sensors VCA and VUS (Series I, kept as the basic set of wind-speed data in the CHMI database), while the second series includes only the UAG measurements (Series II). The standard normal homogeneity test (SNHT) after Alexandersson (1986) and the test introduced by Maronna & Yohai (1978) were applied to the relative homogeneity of those series (with methodology as per Štěpánek et al. 2011, 2013). The reference wind-speed series for the Doksany and Kocelovice stations were always created from 6 surrounding stations, and the pair-wise method (i.e. separately for each station) was used to detect break-points. Because a large number of break-points were not confirmed by metadata, only those that fulfilled the more rigorous criteria derived empirically from homogenisation experience (Štěpánek et al. 2013) were further considered. From comparison of the 2 stations, it follows that the number of break-points in Series I is much higher for Doksany (Table 1) than for Kocelovice (1993 and 1997 for daily means, 1997 for 07:00 and 21:00 h LMT, 1994 and 1998 for 14:00 h LMT), and their number increases from the morning reading at 07:00 h LMT

Table 1. Break-points detected at the Doksany station for Series I of 3 daily readings and daily mean in the 1964–2016 period

Type of series	Break-points (inhomogeneities) detected
0700 LMT	1985, 1990, 1995, 2011
1400 LMT	1981, 1989, 1993, 2011
2100 LMT	1969, 1982, 1985, 1989, 1994, 2002, 2011
Daily mean	1982, 1985, 1990, 1993, 2011

through the day to the evening reading at 21:00 h LMT. Only 2 years exhibit break-points that are close to changes in Vaisala sensors. The year 1997 in Kocelovice coincides with the change of VCA to its 'heated' version. Around 2011, Doksany reported a change from a 15 min interval for averaging instead of the 10 min interval in the previous year (18 February 2010) and the deployment of an ultrasonic sensor in the following year (12 April 2012). All other breaks were not confirmed by the station metadata.

Adjustment of inhomogeneities at the thrice-daily reading and the daily scales was then performed by the authors' adaptation of the Distribution Adjustment by Percentiles method, applied for the correction of regional climate model outputs by Déqué (2007). Our procedure was based on comparison of percentiles (empirical distribution) of differences between adjusted series and related reference series before and after a break. The homogenisation process, including homogeneity testing, evaluation and correction of inhomogeneities detected, was performed in several iterations for both stations analysed.

Fluctuations in final homogenised wind-speed series for individual seasons (as months DJF, MAM, JJA and SON) and annual values for 3 daily readings at 07:00, 14:00 and 21:00 h LMT and daily means appear in Fig. 7. Linear trends and their significance (using *t*-test at significance level $\alpha = 0.05$) were always calculated for corresponding homogeneous Series I and II at the 2 stations (Table 3).

4. RESULTS

4.1. Statistical characteristics of wind speeds

Fig. 4 shows box-plots of comparative wind-speed measurements by UAG and both VCA and VUS Vaisala sensors for the Doksany and Kocelovice sta-

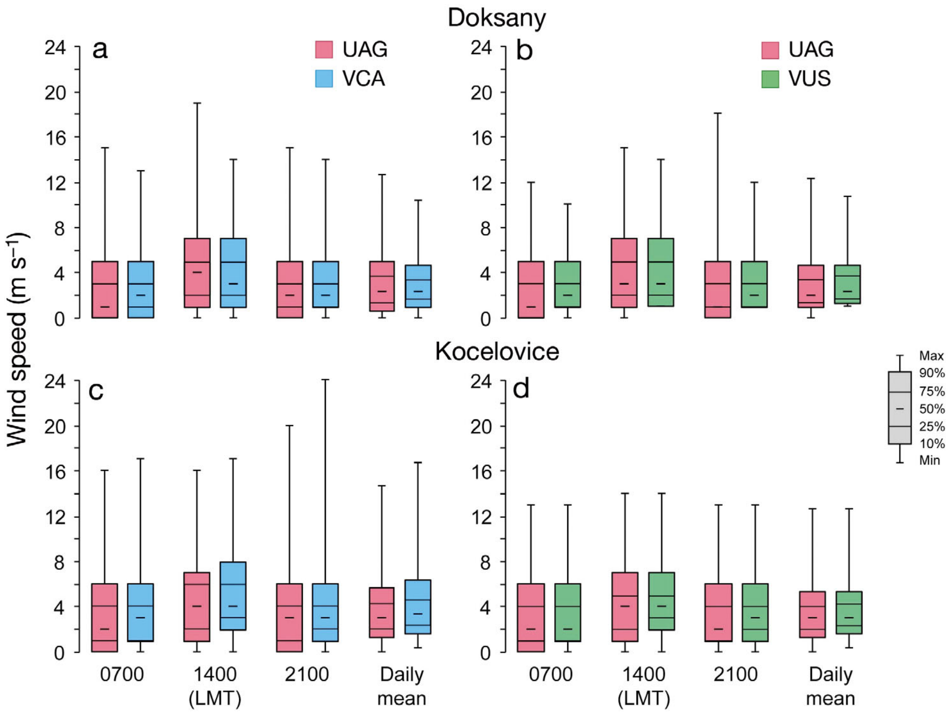

Fig. 4. Box-plots of wind-speeds at 07:00, 14:00, 21:00 h LMT and daily mean from parallel measurements by universal anemograph (UAG) with Vaisala WAA251 cup anemometer (VCA) and with Vaisala WS425 ultrasonic sensor (VUS) at the Doksany and Kocelovice stations. Periods of parallel measurements: UAG – VCA: (a) 1 Apr 2000–11 Apr 2012 at Doksany and (c) 1 Jan 2000–14 Nov 2011 at Kocelovice; UAG – VUS: (b) 12 Apr 2012–31 Dec 2016 at Doksany and (d) 15 Nov 2011–31 Dec 2016 at Kocelovice. Key to box-plots: Max – maximum; 90 % – 90th percentile; 75 % – upper quartile, 50 % – median; 25 % – lower quartile; 10 % – 10th percentile; Min – minimum

tions for series of 3 daily readings at 07:00, 14:00 and 21:00 h LMT and daily mean, which indicate either identical or similar values for basic statistical characteristics.

Table 2. Average wind speeds ± standard deviation (m s^{-1}) for series of parallel wind-speed measurements at 07:00, 14:00, 21:00 h LMT and daily mean at the Doksany and Kocelovice stations (n: number of measurements). Periods of parallel measurements: UAG – VCA: 1 Apr 2000–11 Apr 2012 at Doksany and 1 Jan 2000–14 Nov 2011 at Kocelovice; UAG – VUS: 12 Apr 2012–31 Dec 2016 at Doksany and 15 Nov 2011–31 Dec 2016 at Kocelovice. Abbreviations as in Fig. 4

Instrument	n	Wind speed series			
		07:00 h	14:00 h	21:00 h	Daily
Doksany					
UAG	4391	1.98 ± 2.07	3.91 ± 2.54	2.19 ± 2.07	2.69 ± 1.78
VCA	4391	2.09 ± 1.74	3.74 ± 2.14	2.33 ± 1.78	2.72 ± 1.52
UAG	1724	1.89 ± 2.08	3.74 ± 2.39	1.98 ± 1.97	2.54 ± 1.70
VUS	1724	2.28 ± 1.66	3.75 ± 1.98	2.41 ± 1.64	2.81 ± 1.40
Kocelovice					
UAG	4334	2.76 ± 2.43	4.19 ± 2.44	2.92 ± 2.27	3.29 ± 1.95
VCA	4334	3.10 ± 2.40	4.54 ± 2.44	3.27 ± 2.23	3.64 ± 1.94
UAG	1872	2.76 ± 2.32	4.06 ± 2.33	2.82 ± 2.15	3.22 ± 1.81
VUS	1872	3.00 ± 2.12	4.19 ± 2.19	3.09 ± 1.98	3.43 ± 1.68

In terms of mean wind speeds for the Doksany station (Table 2), both Vaisala instruments give higher values at 07:00 and 21:00 h LMT and in the daily mean, while the average wind speed from the UAG measurements was higher than those from VCA at 14:00 h LMT. When compared with VUS, the averages calculated for 14:00 h LMT from both instruments were nearly identical. The differences in averages between couples of compared instruments are statistically significant except for series of daily means between UAG and VCA and at 14:00 h LMT between UAG and VUS. Data measured by anemograph compared to those produced by Vaisala sensors exhibited higher variability in terms of standard deviation (Table 2). Maximum wind speeds in series of daily readings and daily mean show higher values recorded by UAG compared with both Vaisala instruments in all cases (Fig. 4a,b). Pearson's correlation coefficients between the compared datasets reach statistically significant values (*t*-test, $\alpha = 0.05$) of 0.913–0.944 for VCA and of 0.898–0.949 for VUS (not shown).

Box-plots for the Kocelovice station indicate different results from Doksany. All the statistical characteristics indicate higher values for wind speeds measured by both Vaisala instruments compared to UAG (Fig. 4c,d). This also holds for the means calculated for 4 basic series (07:00, 14:00, 21:00 h LMT and daily means); differences in means between UAG and VCA were higher than between UAG and VUS, and were statistically significant (except for the 14:00 h LMT series for UAG and VUS). While UAG and VCA series show nearly identical variability expressed by standard deviation, wind speeds measured by VUS are more variable than those measured by UAG (Table 2). The corresponding statistically significant Pearson's correlation coefficients between comparative measurements fluctuate in the range of 0.946–0.970 for VCA and 0.944–0.972 for VUS; they are always highest for series of daily means (not shown).

Fig. 5 shows the relative frequencies (%) of daily mean wind speeds that correspond to individual values. At the Doksany station, UAG measurements gave higher frequency for daily wind speeds for those corresponding to 0 and 1 m s^{-1}, while from 2 m s^{-1} to 4 m s^{-1} for VCA (Fig. 5a) and from 2 m s^{-1} to 5 m s^{-1} for VUS (Fig. 5b) higher values were indicated by the Vaisala sensors. Beginning at mean wind speeds of 5 m s^{-1} or 6 m s^{-1}, the frequencies corresponding to UAG are again higher. The highest frequency of mean daily wind speeds is reached at a value of 2 m s^{-1}.

The Kocelovice station discloses a slightly different situation from that at Doksany (Fig. 5c,d). Daily mean wind speeds at values from 0 to 2 m s^{-1} from the UAG measurements are more frequent there, while the relative frequencies calculated from both Vaisala sensors are higher in the 3 m s^{-1} to 7–8 m s^{-1} range. Frequencies for wind speeds ≥ 9 m s^{-1} are more-or-less similar. The highest frequency of mean daily wind speeds is reached for 3 m s^{-1}.

Taking into account wind-speed frequencies from 3 daily readings at the Doksany station (not shown), similar patterns appear for readings at 07:00 and 21:00 h LMT, while data from 14:00 h LMT (with generally higher speeds) differ to some extent. Notable differences appear in relative frequencies for the lowest wind speeds (UAG compared to VCA): 0 m s^{-1} – 27.6:10.1 % (07:00 h LMT), 5.2:1.3 % (14:00 h LMT) and 21.5:7.2 % (21:00 h LMT); 1 m s^{-1} – 25.5:39.7 % (07:00 h LMT), 11.7:12.5 % (14:00 h LMT) and 24.3:34.2 % (21:00 h LMT); 2 m s^{-1} – 14.9:20.3 % (07:00 h LMT), 16.6:19.2 % (14:00 h LMT) and 17.7:22.3 % (21:00 h LMT). This means that only the frequency of speeds 0 m s^{-1} measured by UAG clearly prevails over those measured by VCA. Similarly at Kocelovice, higher frequencies of wind speeds measured by UAG compared with VCA occurred at 0 m s^{-1} (e.g.

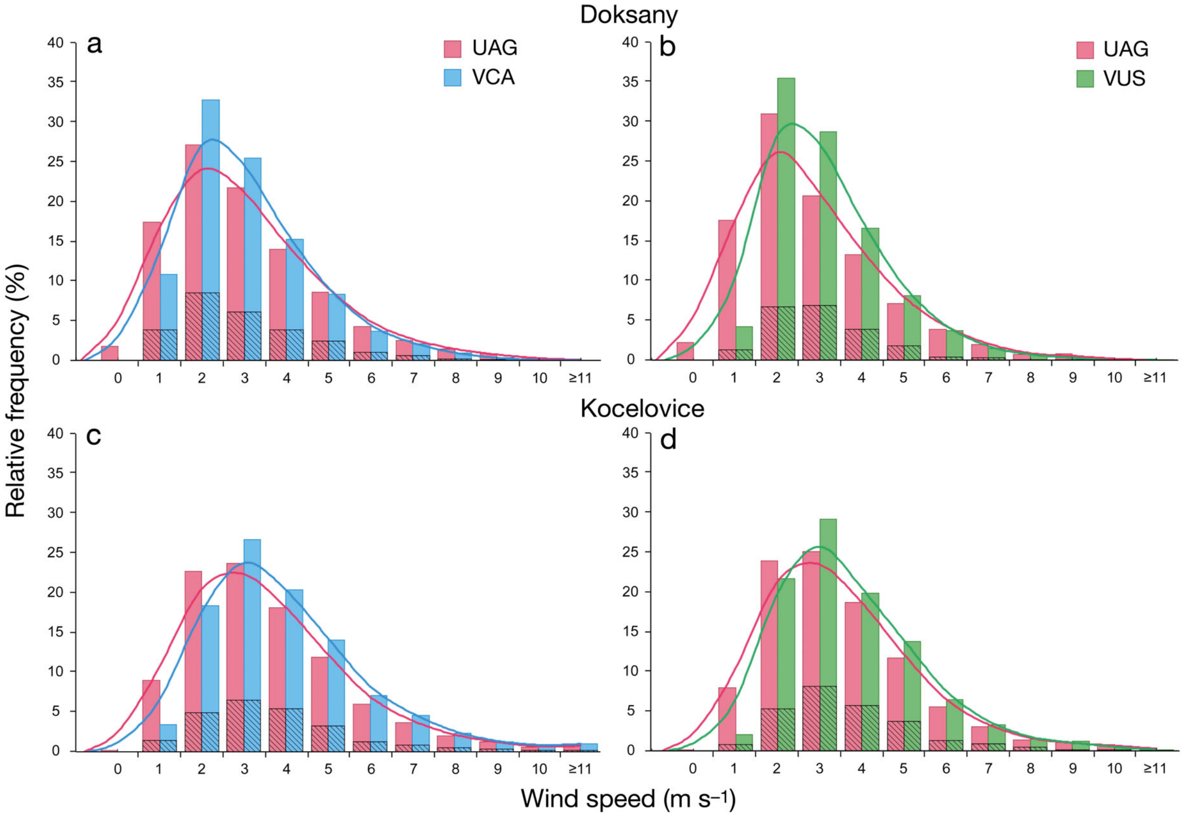

Fig. 5. Histograms of relative frequencies (%) of daily mean wind speeds fitted by appropriate curve from parallel measurements taken by UAG with VCA and with VUS (abbreviations as in Fig. 4) at the Doksany and Kocelovice stations. Periods of parallel measurements: UAG – VCA: (a) 1 Apr 2000–11 Apr 2012 at Doksany and (c) 1 Jan 2000–14 Nov 2011 at Kocelovice; UAG – VUS: (b) 12 Apr 2012–31 Dec 2016 at Doksany and (d) 15 Nov 2011–31 Dec 2016 at Kocelovice. Frequencies of the same mean wind speeds calculated from measurements by both instruments are hatched

17.3:9.5 % at 07:00 h LMT and 11.6:4.5 % at 21:00 h LMT), but also for 1 m s^{-1} (9.9:5.4 % at 14:00 h LMT).

Comparison of UAG and VUS measurements (not shown) reveals that the Vaisala instrument at the Doksany station recorded no calms (compared to the UAG with calm for 26.3 % of all measurements at 07:00 h LMT and 18.8 % at 21:00 h LMT). A similar situation also held for the Kocelovice station, but the differences were not so dramatic (15.0:3.5 % at 07:00 h LMT and 9.7:0.9 % at 21:00 h LMT). At 14:00 h LMT, the UAG at Doksany also recorded higher frequencies for wind speeds of 1 m s^{-1} (14.4:10.3 %; for Kocelovice, this was 9.4:7.0 %). In contrast, significantly higher frequencies recorded by VUS compared to UAG at the Doksany station were detected, particularly for wind speeds of 2 m s^{-1} (23.3:10.7 % at 07:00 h LMT and 27.7:17.4 % at 21:00 h LMT).

4.2. Wind speeds and wind directions

Mean wind speeds calculated for every wind direction (expressed in tenths of a degree) for parallel measurements by the UAG and Vaisala wind-speed sensors at the Doksany and Kocelovice stations are expressed as wind-roses in Fig. 6. The analysis is performed separately for the 2 periods: first for the UAG and VCA (Fig. 6a,c) and second for the UAG and VUS (Fig. 6b,d).

Wind directions of 240°–260° are the most frequent at the Doksany station (15.2 % in the first period and 12.4 % in the second). In both periods, second place is taken by directions 300°–320° (11.8 % and 12.0 %, respectively) and 100°–120° (11.4 % and 11.6 %, respectively) (not shown). Parallel measurements of UAG with VCA gave higher mean wind speeds for the standard instrument for directions 10°–40°, 220°–270° and 320°–340° (maximum 0.28 m s^{-1} for 240°; for 200° and 280°, wind speeds from both instrument sets were the same, see Fig. 6a). For other directions with higher wind speeds measured by automatic anemometer, the maximum difference was 0.46 m s^{-1} for 70°. In terms of daily readings, UAG measured higher speeds for only 8 directions at 07:00 h LMT and for just 6 directions at 21:00 h LMT, but at 14:00 h LMT, the situation was far more pro-

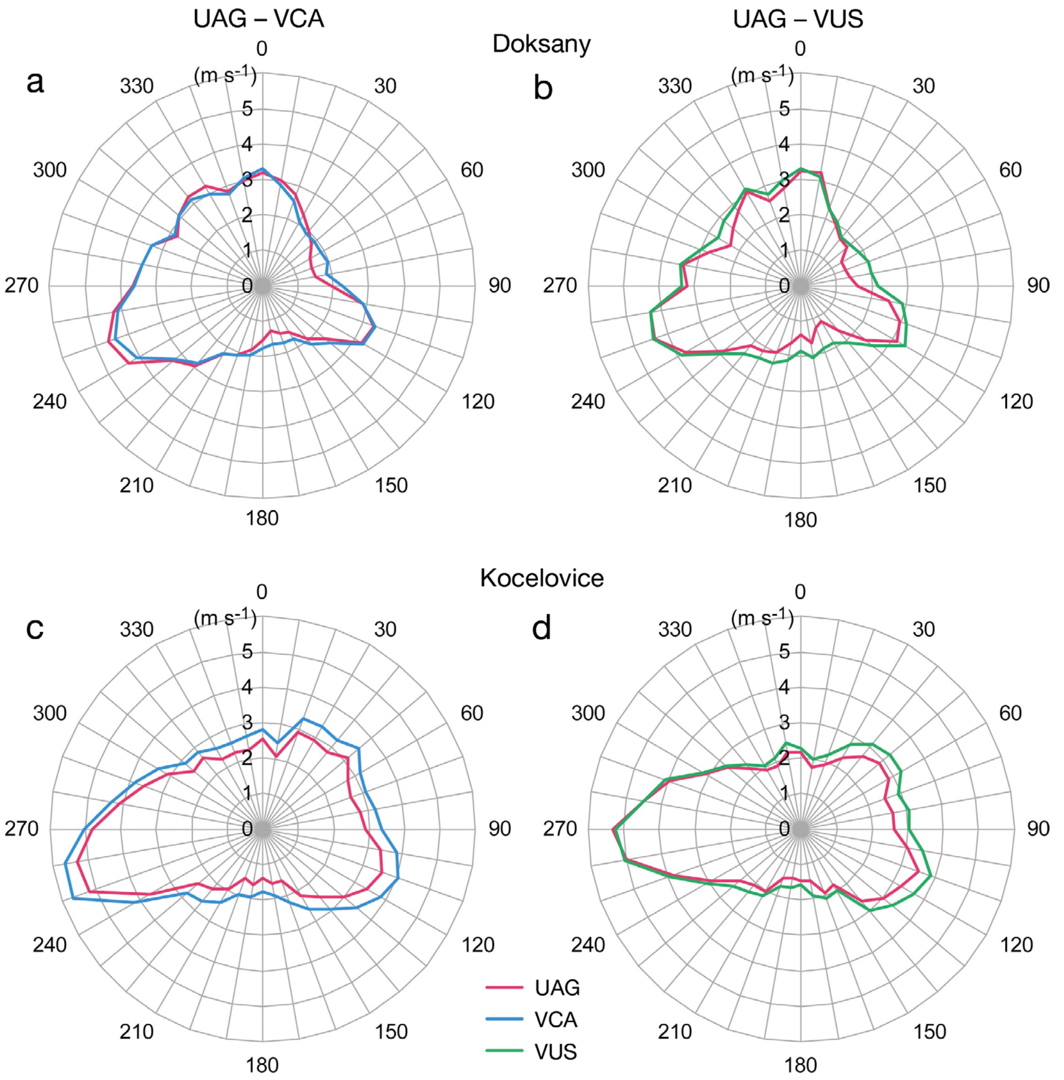

Fig. 6. Wind-roses of mean wind-speeds (m s^{-1}) calculated from the parallel measurements by UAG with VCA and with VUS (abbreviations as in Fig. 4) at the Doksany and Kocelovice stations. Periods of parallel measurements: UAG – VCA: (a) 1 Apr 2000–11 Apr 2012 at Doksany and (c) 1 Jan 2000–14 Nov 2011 at Kocelovice; UAG – VUS: (b) 12 Apr 2012–31 Dec 2016 at Doksany and (d) 15 Nov 2011–31 Dec 2016 at Kocelovice

nounced: higher values were recorded for 22 directions, particularly 200°–340° (not shown). Parallel measurements with VUS yielded a far simpler picture: only for 10° did UAG measure a higher speed, of 0.13 m s^{-1} (also slightly higher for 200° and 280°), while for all other directions, the values measured by VUS were higher (maximum difference 0.69 m s^{-1} for 70°) (Fig. 6b). A similar situation also appeared for the reading at 07:00 h LMT, again with only 3 directions with higher wind-speeds measured by the UAG. While at 14:00 h LMT this held for 16 directions, at 21:00 h LMT the UAG gave lower values than VUS for all directions (not shown).

A westerly flow (260°–280°) prevails at Kocelovice (23.7% in the first comparison period and 24.2% in the second). The mean wind speeds measured by UAG were lower than those of VCA in all directions (differences between 0.20 m s^{-1} for 320° and 0.67 m s^{-1} for 160°) (Fig. 6c). The same situation also held for mean wind-speed roses in the daily readings at 07:00, 14:00 and 21:00 h LMT (not shown). The UAG measurements in comparison with VUS were slightly different for directions between around SW and NW (240°–310°, but also for 330° and 360°), where they differed only between 0.04 and 0.14 m s^{-1} (means for 280° were the same, while UAG measured higher wind-speeds, by 0.08 m s^{-1} for 270°). For the rest of the directions, VUS gave higher wind speeds by 0.2 to 0.4 m s^{-1} (maximum 0.46 m s^{-1} for 80°) (Fig. 6d).

While mean wind-speed roses at readings 07:00 and 21:00 h LMT were similar, at 14:00 h LMT the wind speeds measured by VUS were higher, particularly between 30° and 140° (i.e. between approx. NE and SE), but several other directions (220°–240°, 270°, 280°, 310°, 330° and 360°/0°) gave higher values in the UAG measurements (not shown).

4.3. Long-term fluctuations in wind speeds

Fluctuations in homogenised wind-speed series (07:00, 14:00, 21:00 h LMT, daily mean) of combined UAG and automatic VCA and VUS measurements (Series I) and only UAG measurements (Series II) at the Doksany and Kocelovice stations appear in Fig. 7. These series were used to calculate linear trends,

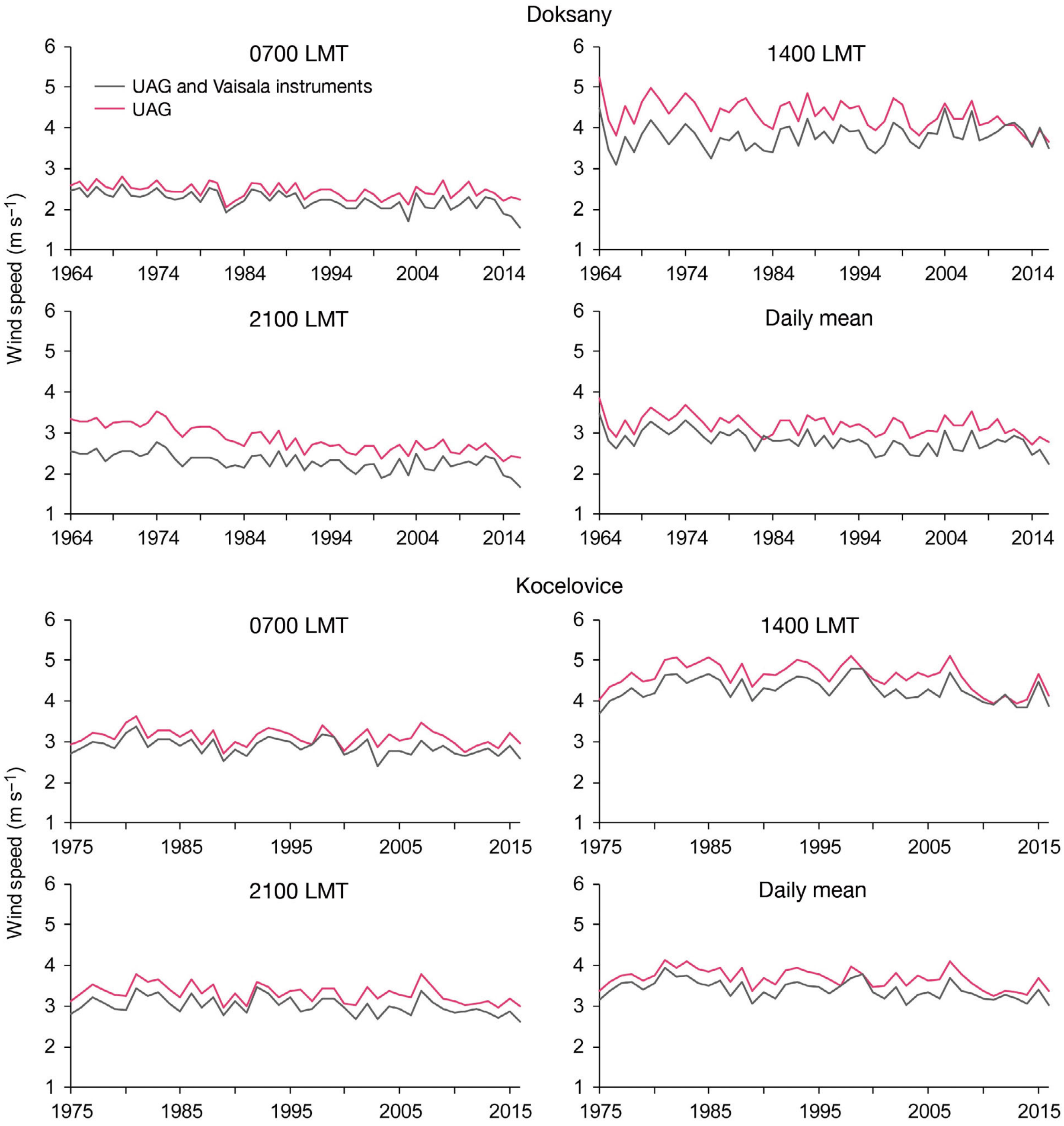

Fig. 7. Homogenised annual series of wind-speeds for 07:00, 14:00 and 21:00 h LMT and daily means at the Doksany (1964–2016) and Kocelovice (1975–2016) stations (black: combined series from the universal anemograph, UAG, and Vaisala instruments; red: UAG)

Table 3. Linear trends in annual and seasonal wind-speed series for daily readings at 07:00, 14:00, 21:00 h LMT and daily mean at the Doksany (Dok; 1964–2016) and Kocelovice (Koc; 1975–2016) stations. Series types: I – UAG combined with Vaisala sensors; II – UAG. Statistically significant trends (significance level α = 0.05) appear in **bold**

Station	Trend (m s^{-1} dec^{-1})				
	Ann	DJF	MAM	JJA	SON
07:00 h LMT					
Dok-I	**–0.049**	**–0.083**	–0.049	–0.009	–0.049
Dok-II	**–0.092**	**–0.102**	**–0.084**	**–0.078**	**–0.095**
Koc-I	–0.043	–0.044	–0.056	–0.026	–0.056
Koc-II	**–0.063**	–0.100	–0.059	–0.021	–0.081
14:00 h LMT					
Dok-I	**–0.108**	**–0.155**	**–0.110**	0.021	**–0.178**
Dok-II	**–0.089**	**–0.119**	**–0.054**	**–0.070**	**–0.103**
Koc-I	**–0.100**	–0.117	–0.097	–0.106	–0.104
Koc-II	–0.049	–0.125	–0.046	–0.015	–0.037
21:00 h LMT					
Dok-I	**–0.180**	**–0.200**	**–0.176**	**–0.170**	**–0.168**
Dok-II	0.035	–0.025	0.056	**0.139**	–0.020
Koc-I	**–0.073**	–0.122	**–0.087**	0.022	**–0.118**
Koc-II	**–0.070**	–0.106	**–0.101**	–0.020	**–0.103**
Daily mean					
Dok-I	**–0.071**	**–0.103**	**–0.081**	–0.020	–0.071
Dok-II	**–0.090**	**–0.102**	**–0.052**	–0.029	**–0.168**
Koc-I	**–0.083**	–0.121	**–0.086**	–0.050	–0.092
Koc-II	**–0.085**	–0.140	**–0.091**	–0.036	–0.089

which appear with their statistical significance based on a *t*-test for α = 0.05 in Table 3.

Morning wind speed measurements at 07:00 h LMT (Table 3, Fig. 7) show generally more marked decreasing trends for UAG Series II compared to combined UAG and Vaisala sensors Series I. While the Dok-II series shows statistically significant trends for annual and all seasonal values (Dok-I for annual and DJF series), none of these series was significant for Koc-I and Koc-II (except annual values).

The afternoon reading at 14:00 h LMT (Table 3, Fig. 7) gives a slightly complicated picture. Significant negative trends were calculated for annual values for Series I from 2 stations and insignificant trends for Series II (for Dok-II with opposite sign). Negative trends for Series I are stronger than those for Series II in seasonal series, with the exception of DJF at Kocelovice. Significant decreasing trends were recorded for all seasonal Dok-I series except JJA. For Dok-II, increasing trends occurred as non-significant for MAM and significant for JJA.

In the series of evening readings at 21:00 h LMT (Table 3, Fig. 7), statistically significant negative trends in Series I and II clearly prevail (insignificant negative only for DJF and positive for JJA at Kocelovice).

In terms of mean daily wind speeds (Table 3, Fig. 7), both series show decreasing trends in annual and seasonal series, which were statistically significant in all annual and MAM series. Significant trends in Series I and II were also found for DJF and in series II for SON at the Doksany station. Taking into account only significant linear trends, Series II shows stronger trends in annual and SON values than Series I, weaker in MAM for Doksany; trends for DJF in both series are nearly identical. Statistically significant negative trends in annual and MAM values do not show any important differences for Kocelovice.

5. DISCUSSION

Although the problems associated with the homogeneity of corresponding series of wind-speed measurements are generally well-known, little attention has been devoted to them from a climatological point of view. For example, DeGaetano (1998) addressed the problem in estimating winds too light for the starting speed of anemometers when investigating the nature of biases in USA surface wind observations. Thomas & Swail (2011) reported difficulties with anemometer types in buoy wind inhomogeneities when creating long-term series. Brázdil et al. (2017b) addressed the question of the possible effects of various wind-speed instruments in explanation of wind-stilling in mean daily wind speeds in the Czech Republic during the 1961–2015 period. The results presented in Section 4 of the current study go significantly beyond the study by Brázdil et al. (2017b), which presented detailed statistical analysis of comparative measurements for 2 Czech stations, with implications for longer-term climatology of wind speeds, but only at the scale of the Czech Republic.

In practice, problems with differences in wind speed measurements in the Czech Republic may be related to the significantly higher starting wind-speed thresholds and over-speeding problems associated with standard cup anemometers (e.g. UAG) compared to low-threshold anemometers (e.g. VCA) or ultrasonic sensors (e.g. VUS) (cf. Brock & Richardson 2001). This was clearly confirmed by this study, particularly by the higher frequency of calms measured by UAG compared to both Vaisala sensors at 07:00 and 21:00 h LMT; in daily means, it appeared in higher frequencies for speeds of 0 and 1 m s^{-1} (see Fig. 5 and Section 4.1). In daily mean wind speeds, it was well-expressed at the Doksany station by higher means measured by the Vaisala sensors at 07:00 and 21:00 h LMT (generally lower wind speeds in daily variation) and lower at 14:00 h GMT (generally higher wind speeds in daily variation), reflected in generally higher mean daily wind speeds calculated for VCA and VUS (see Fig. 4). At the more windy Kocelovice station, mean wind speeds measured by VCA and VUS were higher than those from the Metra anemograph; this tendency was only slightly indicated by a decrease in differences in means between VUS and UAG at 14:00 h LMT.

The results of this comparative analysis of mean wind speeds measured at 2 Czech stations show that changes in instruments may be detected as break-points in wind-speed series. This dictates that homogenisation of such series, on which the quality of final homogenised series is dependent, must be undertaken with great care (see Section 3). From separately-homogenised wind-speed series from UAG alone, or combined UAG and Vaisala sensors (VCA and VUS) measurements, it follows that both types of series for 07:00, 14:00 and 21:00 h LMT differ considerably in linear trends and their significance; however, it is clear that generally decreasing trends prevail in them (cf. Fig. 7, Table 3). The situation is different for homogenised mean daily wind-speed series: their linear trends generally show no important differences in their significance or values (see Table 3 for daily mean). These results are in agreement with broadly observed worldwide wind-stilling (e.g. McVicar et al. 2012, Xiaomei et al. 2012, Chen et al. 2013, Azorin-Molina et al. 2014, 2016, 2017, Dadaser-Celik & Cengiz 2014, Kim & Paik 2015, Romani et al. 2015, Minola et al. 2016, Shi et al. 2016, Brázdil et al. 2017a,b, Guo et al. 2017, Laapas & Venäläinen 2017) and could indicate that the effects of changes in instruments are not significantly reflected in decreasing trends of mean daily wind-speeds in the Czech series at least at lower and mid-altitudes (i.e. for 81.5% of stations involved in the study by Brázdil et al. 2017b). The use of only 2 stations, however, introduces bias, and consequent high uncertainty, into this speculation.

Further uncertainties in the process of wind-speed measurement arise from the accuracy (or otherwise) of wind-speed readings. Rounding measured values to full integers clearly influences the results of comparative measurements. Moreover, Azorin-Molina et al. (2017), studying trends in daily wind speeds for selected Spanish stations during the 1961–2011 period, also addressed the problem of the time intervals from which wind-speed means are calculated. They found stronger negative trends for annual and seasonal series of daily wind speeds calculated from 4 synoptic readings (63.2% of stations with wind-stilling) compared to those calculated from 24 h wind-run measurements (36.8%).

6. CONCLUSIONS

From statistical analysis of parallel wind speed measurements taken by UAGs and Vaisala sensors at the Doksany and Kocelovice stations, the following conclusions may be reported:

(1) Vaisala sensors measure, on average, higher wind speeds in the morning (07:00 h LMT) and evening (21:00 h LMT) and in daily means compared to UAGs (at 14:00 h LMT in Doksany, the situation is opposite); differences in means from both types of instruments fluctuate between 0.0 to 0.4 m s^{-1}.

(2) Because of the rounding of measured wind speeds to full integers, the lower starting wind-speed threshold of automatic instruments significantly increases the number of speeds of 1 m s^{-1} recorded by Vaisala sensors compared to the number of speeds of 0 m s^{-1} recorded more frequently by the UAG.

(3) Differences in wind-speeds between the UAG and Vaisala sensors do not show any systematic dependence on wind direction, although higher values measured by automatic sensors are more frequent.

(4) Changes in instruments from UAG to Vaisala VCA and VUS sensors could generate break-points in wind-speed series. Linear trends of homogenised daily mean wind-speed series from only the UAG or combined from the UAG and Vaisala sensors generally show no important differences in their significance or values. This could indicate that effects of changes in instruments used would not be significantly reflected in decreasing trends ('stilling') of mean daily wind-speeds in the Czech series; however, the fact that only 2 stations were used for comparison may make for high uncertainty in this statement.

(5) The conclusions in the preceding point are not valid for homogenised series of wind speeds at 3 daily readings (07:00, 14:00, 21:00 h LMT), which show important differences in linear trends and their significance between the 2 types of series (instruments).

The results presented fully confirm anticipated differences in wind-speed measurements related to the higher wind-speed threshold of standard cup anemometers (e.g. UAG) compared to low-threshold anemometers (e.g. VCA) or ultrasonic sensors (e.g. VUS), while the over-speeding effect of standard cup anemometers was expressed more weakly. This means that, despite careful homogenisation, missing or only sporadic comparative measurements during replacement of wind-speed instruments may point to serious problems in wind-speed series, particularly with respect to their medium- or long-term trends.

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