Vol. 77: 1–21, 2019
https://doi.org/10.3354/cr01540

CLIMATE RESEARCH
Clim Res

Published online January 8

Forcings and projections of past and future wind speed over the Czech Republic

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ABSTRACT: Monthly, seasonal and annual wind-speed series from 119 meteorological stations in the Czech Republic indicate significant decreasing trends in the period 1961–2015. Attribution analysis, applying multiple linear regression, was used to identify wind-speed components related to natural and anthropogenic climate forcings and internally induced climate variability. A significant link to wind speeds was detected for the North Atlantic Oscillation index, as well as for the closely-related Central European Zonal index, especially during the winter. An influence from the East Atlantic/Western Russia Pattern was found during autumn and winter, especially in the eastern part of the country. Changes in large-scale circulation did not seem to be primarily involved in long-term wind stilling, despite a formal correlation between the stilling and anthropogenic forcing. Distinct geographical variations in the regression-estimated links suggest profound influences from interactions between local features of the measuring sites and large-scale climate-forming factors. In total, 11 Euro-CORDEX regional climate model (RCM) simulations for representative concentration pathways RCP4.5 and RCP8.5 were used for projection of annual and seasonal mean daily wind speeds for the Czech Republic for 1951–2100. Despite correction of the model biases for individual RCMs, these simulations largely underestimated the magnitude of declining observational trends in 1981–2010, with only annual, winter and spring values sharing the same trend for both RCPs. Linear trends in wind speeds calculated for 1981–2100 for both RCPs show a significant negative trend in summer, while significant positive trends in winter and spring wind speeds were recorded for RCP8.5.

KEY WORDS: Wind speed · Climate forcings · Circulation indices · Attribution analysis · Wind-speed projections · Regional climate models · Czech Republic

1. INTRODUCTION

Worldwide analyses of wind-speed series for the last 30–50 yr demonstrate statistically significant decreases, particularly in land mid-latitudes (e.g. Smits et al. 2005, McVicar et al. 2008, 2012, Pryor et al. 2009, Vautard et al. 2010, Guo et al. 2011, Péliné Németh et al. 2011, Yang et al. 2012, Chen et al. 2013, Azorin-Molina et al. 2014, 2016, 2017, Dadaser-Celik & Cengiz 2014, Kim & Paik 2015, Romanić et al. 2015, Minola et al. 2016, Shi et al. 2016, Guo et al. 2017, Laapas & Venäläinen 2017), for which the term 'stilling' has come to be used (Roderick et al. 2007). Various reasons for this development have been proposed in the literature (for a summary, see McVicar et al. 2012), but exact quantification and proofs remain difficult to establish. Increasing surface roughness may be especially responsible for the effect. For

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example, Wever (2012) calculated the local roughness length for 157 meteorological stations of 8 European countries and showed that it doubled during the period 1962–2009. Applying the conceptual boundary-layer model, 70% of the wind-speed trend may be attributed to roughness changes. Earlier Vautard et al. (2010) reported an observed wind-speed decrease at 822 stations in the northern mid-latitudes during 1979–2008 and attributed 25–60% of it to increased surface roughness and 10–50% to atmospheric circulation.

Other contributions have attempted to explain current existing decreasing trends in changes in atmospheric circulation in terms of circulation indices such as the North Atlantic Oscillation index (NAOI) (e.g. Brázdil et al. 2009, 2017a,b, Azorin-Molina et al. 2014, Minola et al. 2016) or of changes in major pressure systems (Romani et al. 2015). However, rather limited attention has been paid to the effects of climate forcings in wind-speed fluctuations, which can manifest either directly or via changes in large-scale circulation modes. Among the related studies, Zwiers & Kharin (1998) linked the increase in CO_2 concentration and the resulting reduction of pole-to-equator temperature gradient to a decrease in globally averaged wind speed, though with a possibility of increased wind speed extremes over Europe. Ulbrich & Christoph (1999) joined increasing forcing of greenhouse gases (GHGs) with a change in the NAO patterns. Bichet et al. (2012) explained the wind-speed decline in the past 30 yr in the northern mid-latitudes not only in terms of increased roughness, but also through other forcings (atmospheric aerosols, sea surface temperature [SST] and GHG concentrations) over the longer term. Gray et al. (2013) reported a time-lagged response of sea level pressure over Europe and Northern Atlantic to the 11 yr solar cycle; Gray et al. (2016) then analysed the effects of the solar cycle on the NAO and the Atlantic-European blocking. Schwander et al. (2017) pointed out changes in airflow over Central Europe depending on low/high solar activity. Furthermore, Swingedouw et al. (2017) demonstrated that effects of tropical volcanic eruptions of the same magnitude or weaker than the 1991 Mt. Pinatubo eruption on the NAO and ENSO are hard to detect (due to strong noise stemming from natural climate variability), while clear volcanic effects appear in the Atlantic Multidecadal Oscillation index (AMOI). Overall, the uncertainty regarding the influence of external forcing to atmospheric circulation remains high, and stronger confidence regarding circulation-related aspects of climate change may be challenging to obtain (Shepherd 2014).

Series of mean daily wind speeds and maximum wind gusts showing decreasing trends have also been reported for the Czech Republic in Central Europe (Brázdil et al. 2009, 2017a,b). Further, these contributions demonstrated close relationships between wind speeds/gusts and circulation patterns such as the NAOI (Jones et al. 1997) and the Central European Zonal index (CEZI) (Jacobeit et al. 2001), particularly for the winter half-year (October–March).

As reported by Bichet et al. (2012), wind-speed trends simulated by the ECHAM5 global climate model underestimate those established by observations over land and ocean. High-resolution regional climate models (RCMs) are far less frequently applied to simulations of wind-speed fields compared with other climate variables such as temperature or precipitation (see e.g. Jacob et al. 2014, Kotlarski et al. 2014, Štěpánek et al. 2016). This is also confirmed by an overview of models used for projection of future storminess in the North Atlantic European region by Mölter et al. (2016), in which the use of RCMs lags considerably behind that of general circulation models (GCMs). For example, wind-speed RCM simulations were employed by Rockel & Woth (2007) to demonstrate the effects of increasing GHG concentrations on windiness in Europe, and by Beniston et al. (2007) to show an increase in extreme wind speeds for winter storms between latitudes 45° and 55° N. Donat et al. (2010b) applied RCMs to investigate the spatial patterns of wind speeds and their loss potentials during severe winter storms (for similar studies estimating future wind loss potential, see e.g. Donat et al. 2011, Pinto et al. 2012, Gerstengarbe et al. 2013). Walter et al. (2006) studied the extent to which RCMs could simulate spatio-temporal variability over Germany, while future projections for monthly wind speeds were investigated in terms of extreme wind speeds by Kunz et al. (2010). Nikulin et al. (2011) applied an ensemble of RCM simulations to future projections of wind extremes over Europe. Further, RCMs may produce territorially different tendencies, as shown for future wind gusts in Germany by Rauthe et al. (2010) and for future wind energy sources in Europe by Tobin et al. (2015) and Carvalho et al. (2017).

In order to extend existing analyses of wind speeds over the Czech Republic, this paper concentrates on the effects of climate forcings, in terms of their fluctuations, and on wind-speed projections for the 21st century based on an ensemble of model projections for 2 representative concentration pathways (RCPs): RCP4.5 and RCP8.5 (van Vuuren et al. 2011). Better knowledge of forcings should facilitate a deeper understanding of, and contribute to, the evaluation of climate model outputs.

2. DATA

2.1. Wind-speed series

For the analysis, we selected a series of mean daily wind speeds (MDWSs) from 119 meteorological stations of the Czech Hydrometeorological Institute (CHMI) from across the Czech Republic and covering the period 1961–2015. First, the MDWS series were qualitatively checked to detect outliers. The standard normal homogeneity test (Alexandersson 1986) and the Maronna & Yohai test (Maronna & Yohai 1978) were used to test their relative homogeneity, following the methodology by Štěpánek et al. (2011). The 6 stations best correlated to the candidate station were always selected for reference and were employed for 'pairwise' detection. Break-points detected in candidate series were further evaluated with respect to station metadata. Distribution adjustment by percentiles, used in the correction of regional climate model outputs by Déqué (2007), was adapted to adjust recognised non-homogeneities on a daily scale. This approach is based on comparison of percentiles (empirical distribution) of differences (or ratios) between candidate and reference series before and after a break. Homogeneity testing, evaluation and correction of non-homogeneities were performed in several iterations. Any missing data were later filled in for MDWS series (for more detail, see Štěpánek et al. 2013). Homogenised series from the 119 meteorological stations in the Czech Republic had already been used for study of the spatial and temporal variability of MDWSs in the 1961–2015 period (Brázdil et al. 2017b).

To complement the assessment of variability detected in station-based wind-speed series with results pertaining to free atmospheric circulation, wind-speed components at the 850 hPa level were adopted from NCEP/NCAR reanalysis data (Kalnay et al. 1996). For the tests presented herein, reanalysis series covering the same period as the observational data were employed, i.e. 1961–2015.

2.2. Forcing series

While the presence of distinct linear trends in many of the Czech wind-speed series is well established (Brázdil et al. 2009, 2017a,b; Fig. 1), the questions of their origins and causal relations to climate-forming factors remain open. As previously shown by numerous studies, many diverse factors have the potential to contribute to observed patterns of climate variability (e.g. Stocker et al. 2013). Some of these are related to the activity of external climate forcings, either natural (including variations in solar and volcanic activity) or anthropogenic (such as changes in quantities of GHGs and aerosols) (cf. Stocker et al. 2013). Others may arise out of manifestations of internally induced climate variability. For the Central European region, the NAO is considered to be the most influential, leaving marked imprints in the records of a range of climate variables as well as in many related quantities (e.g. Beranová & Huth 2007, Brázdil et al. 2009, 2012, 2017b, Donat et al. 2010a, Pokorná & Huth 2015). Other oscillatory systems have been shown to project teleconnections to the European region, albeit generally less prominent in both magnitude and statistical significance. These include the ENSO system and the related Pacific Decadal Oscillation (PDO), as well as the Atlantic Multidecadal Oscillation (AMO) (see e.g. Brázdil & Bíl 1998, Brönnimann et al. 2007, Mikšovský et al. 2014, 2016). In Europe, less attention has been devoted to the effects of the East Atlantic/Western Russia Pattern (EA/WRP; Barnston & Livezey 1987), although Ionita (2014) reported its strongest impacts on precipitation in mid-winter and early spring over the Scandinavian Peninsula and the central and eastern parts of Europe, as well as a link between mid-winter EA/WRP and European temperature (see also Krichak et al. 2002, Krichak & Alpert 2005, Nesterov 2009). In our study, the presence of wind-speed components attributable to these various forms of external and internal forcings was addressed by means of multi-variable linear regression analysis, employing up to 10 explanatory variables.

Potential formal links between wind speeds and global changes in anthropogenic radiative forcing were investigated by means of a predictor series embodying CO2EQ, approximating the aggregate effects of anthropogenic GHGs and aerosols (Meinshausen et al. 2011; data downloaded from www.pik-potsdam.de/~mmalte/rcps/). It should be noted, however, that interpretation of the formal links between anthropogenic forcings and wind speed must be made with great caution, as further discussed in Section 5.1.

To assess the possible effects of natural external climate forcings, variations of solar activity were considered through series of solar irradiance (SOLAR) calculated using the Naval Research Laboratory (NRL2) solar irradiance model and obtained through

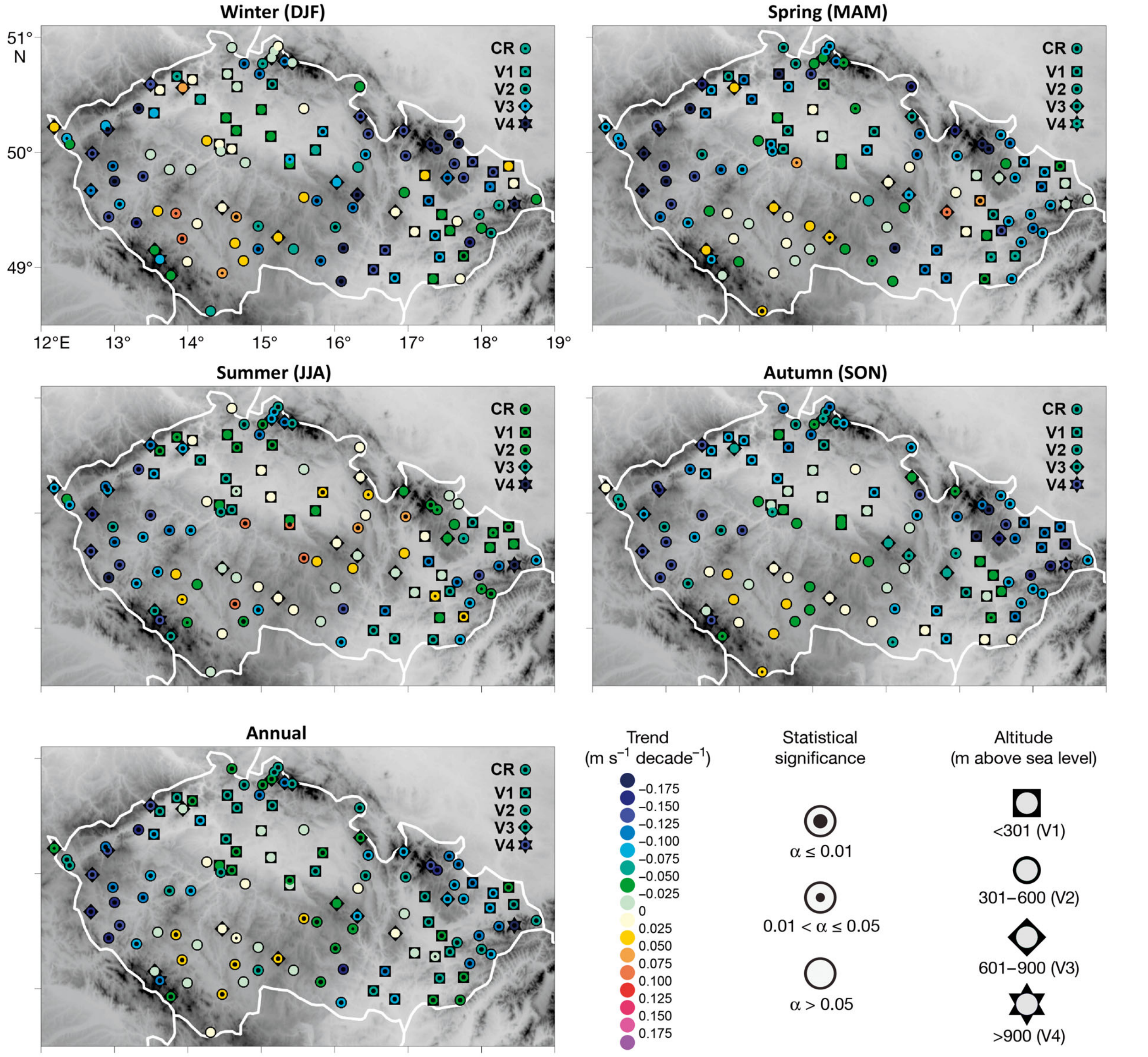

Fig. 1. Seasonal and annual linear trends in mean daily wind speeds (MDWSs) and their statistical significance at 119 meteorological stations, divided into 4 altitudinal intervals (V1–V4) over the Czech Republic (CR) in the period 1961–2015

the Climate Explorer (CLIMEXP) database at https://climexp.knmi.nl/data/itsi_ncdc_monthly.dat. Volcanic aerosol optical depth series for the Northern Hemisphere, obtained from the National Aeronautics and Space Administration, Goddard Institute for Space Studies (http://data.giss.nasa.gov/modelforce/strataer/) (Sato et al. 1993), were used as proxies for volcanic activity (VOLC).

Scalar indices of 6 climate variability modes were used to characterize the phases of the internal climate oscillations selected. For the NAO, we used the NAOI, an index derived from normalized air pressure differences between Gibraltar and Reykjavik, provided by the Climate Research Unit (CRU), Norwich (www.cru.uea.ac.uk/cru/data/nao/) (Jones et al. 1997). As a potential alternative to NAOI, the Arctic Oscillation index (AOI) was also considered among the explanatory variables, obtained from NOAA (www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/monthly.ao.index.b50.current.ascii). The EA/WRP index (EA/WRPI), representing yet another climate variability mode affecting European weather variability, was used in the version provided by NOAA (ftp://ftp.cpc.ncep.noaa.gov/wd52dg/data/indices/eawr_index.tim). The phase of the ENSO was characterized by the Southern Oscillation index (SOI), i.e. the index of its atmospheric component, obtained from CRU at https://crudata.

uea.ac.uk/cru/data/soi/ (Ropelewski & Jones 1987). The potential teleconnections originating in the Pacific area were further considered by including the Extended Reconstructed Sea Surface Temperature (ERSST)-based Pacific Decadal Oscillation index (PDOI), obtained from the CLIMEXP database (http://climexp.knmi.nl/data/ipdo_ersst.dat). The effects of SST variability in the northern Atlantic Ocean were studied through the AMOI, in a version generated by linear detrending of mean SST in the northern Atlantic (Enfield et al. 2001) and provided by NOAA (https://www.esrl.noaa.gov/psd/data/timeseries/AMO/). The inclusion of AMO in this analysis was motivated by an interest in responses to short-to-mid-term variations in the North Atlantic SST rather than an attempt to identify reliably the imprint of the approximately 70 yr cycle associated with this oscillation (Enfield et al. 2001); a version of AMOI without temporal smoothing was therefore employed.

Finally, attention was also paid to the link between wind speeds and the CEZI (Jacobeit et al. 2001). Defined as the difference in standardized 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, this index is closely related to regional circulation over Central Europe, including the Czech MDWSs (Brázdil et al. 2017b). Unlike the 6 previously-mentioned indices, this quantity is not associated with any established large-scale mode of internal climate variability. However, it may serve as a convenient quantifier of the north–south pressure gradient over Central Europe, and thus as a predictor of the speed of (especially) zonal winds.

2.3. Climate models

RCM simulations, prepared within the European part of the Coordinated Regional Climate Downscaling Experiment (CORDEX, www.cordex.org), produce a set of climate change projections for individual world regions and various RCPs (van Vuuren et al. 2011). Outputs of GCMs, obtained from the Coupled Model Intercomparison Project (CMIP5) (Taylor et al. 2012), were used as a source of driving data for the RCMs. The European domain of CORDEX, the Euro-CORDEX subproject (Jacob et al. 2014; www.euro-cordex.net), employed 10 different RCMs and 13 driving GCMs.

The following RCMs, with 0.11° resolution experiments forced by RCP4.5 and RCP8.5, were used in this study: ALADIN53 (Centre National de Recherches Météorologiques, Météo France), CCLM4-8-17 (COSMO Climate Limited-area Model), HIRHAM5 (Danish Meteorological Institute), RACMO22E (Royal Netherlands Meteorological Institute) and RCA4 (Rossby Centre regional Atmospheric model). Two of the 5 RCMs were driven by more than 1 GCM. Models CCLM4-8-17 and RCA4 are driven by 3 and 5 GCMs, respectively, i.e. a total of 11 Euro-CORDEX experiments are available (Table 1; cf. Štěpánek et al. 2016). The selection of experiments was based on their availability in 2016.

3. METHODS

3.1. Attribution analysis

Multiple linear regression (e.g. Wilks 2011) was employed as the basic tool of statistical attribution analysis. Using the predictors introduced in Section 2.2, or specific sub-sets of these predictors, regression coefficients between the MDWS series (for 119 individual meteorological stations as well as for their areal mean over the Czech Republic) were calculated by application of the least-squares method. To facilitate intercomparison of the results between different locations and predictors, the regression coefficients are presented here in a standardized form, i.e. equivalent to a setup with all predictor and predictand time series transformed in linear fashion to 0 mean and SD = 1. The statistical significance of the regression coefficients was evaluated by moving-block bootstrapping, with a block size of 3 mo, chosen to account for the autoregressive structures detected in the regression residuals. To suppress the influence of the annual cycle-related components in the predictands and predictors, the mean annual cycle was subtracted from the monthly wind-speed series prior to analysis. The following abbreviations denote individual seasons: DJF: winter, MAM: spring, JJA: summer, SON: autumn.

3.2. Wind-speed projections

Because simulated climate exhibits systemic deviations from observed climate, climate model outputs must be post-processed to obtain the optimal fit with observed climate (Maraun 2013). Various methods of bias correction have been developed. Overall comparison of papers addressing the methods of comparison indicates that quantile mapping techniques usually perform the best (e.g. Themessl et al. 2011,

Table 1. Euro-CORDEX regional climate model (RCM) experiments employed herein and their driving general circulation models (GCMs). For all RCMs, scenarios tested were representative concentration pathways (RCPs) 4.5 and 8.5

RCM	Driving GCM	GCM origin/name	GCM ensemble member
ALADIN53	CNRM-CM5	Centre National de Recherches Météorologiques	r1i1p1
CCLM4-8-17	CNRM-CM5	Centre National de Recherches Météorologiques	r1i1p1
	EC-EARTH	EC-Earth consortium	r12i1p1
	MPI-ESM-LR	Max Planck Institute – Earth System Model – Low Resolution	r1i1p1
HIRHAM5	EC-EARTH	EC-Earth consortium	r3i1p1
RACMO22E	EC-EARTH	EC-Earth consortium	r1i1p1
RCA4	CNRM-CM5	Centre National de Recherches Météorologiques	r1i1p1
	EC-EARTH	EC-Earth consortium	r12i1p1
	HadGEM2-ES	Hadley Global Environment Model – Earth System	r1i1p1
	IPSL-CM5A-MR	Institut Pierre-Simon Laplace Earth System Model (Medium Resolution)	r1i1p1
	MPI-ESM-LR	Max Planck Institute – Earth System Model – Low Resolution	r1i1p1

Teutschbein & Seibert 2013). In our study, the distribution adjustment by percentiles method (based on quantile mapping) was applied for bias adjusting, on a daily basis and for each grid cell/location separately. Note that even though the method has the same name as the homogenisation method, derived from the same methodology, it is applied in a different way, from a technical point of view. Where station data are preferred (and because they are also available for the current climate), they have been rendered suitable for impact studies by correction/localization performed by finding the nearest grid points for a given location (station) and applying the correction several times. Final corrections are taken from the nearest (reference) series. However, we have also run corrections for further neighbours (correction is performed for the station position, using 10 surrounding grid points). This then serves for analysis if all the corrected series (run individually for all of the neighbours) are in accordance (spread of corrections using different grid points is not large, i.e. uncertainty is low). The advantage of this method is that it does not presume any statistical distribution and is thus more flexible in its application (and even quite robust, given the limited length of the time period).

A highly voluminous range of MDWSs was generated by individual RCM simulations, so ensemble means smoothed by a 10 yr Gaussian filter were used for their presentation in the period 1951–2100 for RCP4.5 and RCP8.5 (see Figs. 10 & 11). Linear regression was used to calculate linear trends, which were assessed for statistical significance via a *t*-test (level of significance $\alpha = 0.05$).

4. RESULTS

4.1. Climate forcings in MDWS series for 1961–2015

Fluctuations in Czech annual MDWS series in the period 1961–2015, calculated as a mean of MDWS series from 119 meteorological stations, are presented in Fig. 2 in comparison with fluctuations in individual climate forcings. A clearly decreasing, significant ($\alpha = 0.05$) linear trend of –0.061 m s^{-1} decade^{-1} is typical of the annual MDWSs, similar to the trend for individual seasons, fluctuating between –0.044 m s^{-1} decade^{-1} in JJA and –0.069 m s^{-1} decade^{-1} in DJF (Fig. 1; see Brázdil et al. 2017b for a more detailed analysis).

Among individual forcings, a significant increasing trend is present for series of CO_2-equivalent concentration, while other explanatory variables exhibit more complex behaviour, ranging from episodic events associated with volcanic activity and a near-periodic cycle combined with long-term evolution of solar irradiance, to fluctuations in various frequencies found in the relevant indices of internal climate oscillations (Fig. 2).

As the correlation overview in Table 2 shows, there are noteworthy similarities between the series of Czech MDWSs and some of the predictors, as well as among the explanatory variables themselves. A strong formal link may be found between MDWSs and anthropogenic forcing, due to similarities in their long-term components (note that this relation is substantially more pronounced for the smoothed versions of the series, i.e. when the short-term fluctua-

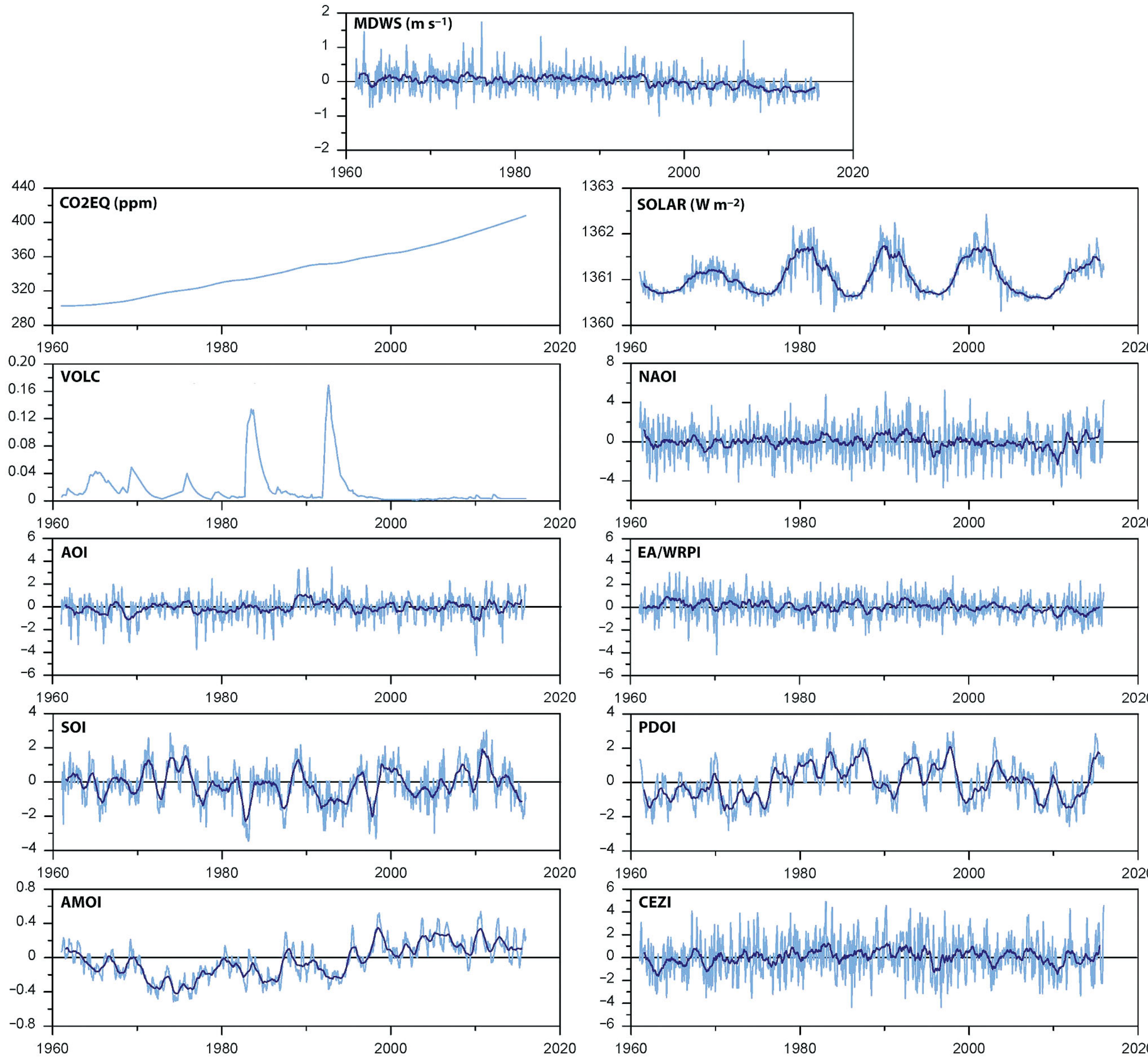

Fig. 2. Fluctuations in monthly series of mean daily wind speeds (MDWSs) for the Czech Republic and in the series of individual explanatory variables over the period 1961–2015. Darker line: smoothed by 13 mo running means (except CO2EQ and VOLC). Variables are defined in Table 2

tions in the MDWS series are suppressed). On the other hand, the connections between MDWSs and NAOI/AOI/CEZI result largely from synchronisation of their month-to-month variations. There are also marked correlations between anthropogenic forcing and the AMOI (largely stemming from the increased AMOI between the 1970s and 1990s), between the SOI and the PDOI (resulting from a connection between related processes in the Pacific area) and between NAOI and CEZI (reflecting the strong association of local circulation over Central Europe with the NAO-related pressure anomaly dipole over the northern Atlantic). Regardless of their origin, the presence of these inter-predictor correlations (i.e. multicollinearity) has an important effect on the interpretation of the outcomes of the regression analysis, as further discussed in Section 5.1. Several of the correlations are also subject to marked seasonal variations (see Table S1 in the Supplement at www.int-res.com/articles/suppl/c077p001_supp.pdf). In particular, the link between MDWSs and NAOI/AOI/CEZI, which is quite prominent during boreal winter, is substantially diminished during the warm part of the year. For this reason, the attribution analy-

Table 2. Pearson correlation coefficients between series of mean daily wind speed (MDWS) for the Czech Republic and series of individual explanatory variables in the period 1961–2015. Monthly series are shown above the main diagonal; annual means are below the diagonal. Values significant at the 95% level appear in **bold** type; correction for temporal persistence in the time series was applied (Bretherton et al. 1999). CO2EQ: CO_2-equivalent concentration; SOLAR: solar irradiance; VOLC: volcanic activity; NAOI: North Atlantic Oscillation index; AOI: Arctic Oscillation index; EA/WRPI: East Atlantic/Western Russia Pattern index; SOI: Southern Oscillation index; PDOI: Pacific Decadal Oscillation index; AMOI: Atlantic Multidecadal Oscillation index; CEZI: Central European Zonal index. For season-specific correlation values, see Table S1 in the Supplement

	MDWS	CO2EQ	SOLAR	VOLC	NAOI	AOI	EA/WRPI	SOI	PDOI	AMOI	CEZI
MDWS		**−0.29**	−0.04	**0.19**	**0.15**	**0.14**	−0.06	−0.04	0.01	**−0.20**	**0.30**
CO2EQ	**−0.73**		0.11	−0.23	−0.03	0.09	**−0.16**	0.00	0.13	**0.55**	0.05
SOLAR	−0.12	0.13		−0.05	**0.13**	**0.10**	−0.07	−0.05	0.07	0.06	**0.15**
VOLC	**0.45**	−0.25	−0.05		**0.09**	0.02	**0.11**	**−0.19**	0.24	−0.30	0.05
NAOI	0.22	−0.09	**0.33**	0.24		**0.63**	0.06	0.00	0.01	**−0.16**	**0.70**
AOI	−0.04	0.22	0.20	0.04	**0.68**		**0.11**	**0.11**	**−0.14**	−0.08	**0.54**
EA/WRPI	**0.35**	**−0.45**	−0.17	**0.37**	**0.31**	0.22		−0.07	−0.03	**−0.17**	−0.03
SOI	−0.10	−0.01	−0.10	**−0.32**	−0.22	0.05	−0.26		**−0.43**	−0.01	−0.02
PDOI	0.13	0.17	0.11	0.31	0.05	−0.15	0.02	**−0.64**		0.05	0.05
AMOI	**−0.57**	**0.62**	0.10	−0.34	**−0.28**	−0.15	**−0.50**	0.02	0.08		−0.09
CEZI	0.20	0.14	**0.38**	0.16	**0.69**	**0.62**	0.10	−0.15	0.16	−0.05	

sis was carried out not only for the year as a whole, but also for individual seasons defined in the usual climatological sense.

Applying multiple linear regression to Czech MDWSs and the set of 9 explanatory variables (CO2EQ, SOLAR, VOLC, NAOI, AOI, EA/WRPI, SOI, PDOI, AMOI), standardized regression coefficients are presented in Fig. 3a. In contrast to the strong link between CO_2-equivalent GHG concentration and MDWS, no detectable component in the MDWS is associated with variations in solar activity. On the other hand, a relationship between wind speed and volcanic activity is suggested by the regression mappings, albeit statistically significant only for certain seasons. The influence of SOI is generally weak in the MDWS series, and is relatively strongest (borderline significant) during the MAM season. Components from AMOI and PDOI are generally weak and non-significant; their inclusion is also problematic in view of the relative shortness of the period under analysis (55 yr) compared to the typical time-scales for multidecadal variations in the Atlantic and Pacific area. In the subsequent analyses, PDOI and AMOI were therefore not included as predictors.

In addition to the 9 explanatory variables representing either external forcing or established large-scale climate variability modes (Fig. 3a), multiple linear regression was also applied to a set of predictors extended by CEZI (Fig. 3b). This inclusion substantially increases the fraction of variance explained by the regression model. However, the use of 3 strongly correlated (and physically related) explanatory variables in the form of CEZI, NAOI and AOI introduces a strong multicollinearity to the regression model, with an adverse effect on the stability of the model and conveys uncertainty into the respective regression coefficients. Additional tests were therefore carried out to reduce the number of predictors; a combination of NAOI and CEZI was found to explain most of the variance in the wind-speed data, while AOI proved largely redundant (cf. Fig. 3b,c). The follow-up analysis of wind-speed data at individual weather stations was then carried out with a total of 7 predictors: CO2EQ, SOLAR, VOLC, NAOI, EA/WRPI, SOI and CEZI, i.e. the predictor configuration employed in Fig. 3c.

In order to characterize geographical peculiarities involved in the effects of selected explanatory variables, multiple linear regression was also applied separately to the monthly MDWS series of the 119 individual meteorological stations. Some basic features following from standardized regression coefficients appear in Fig. 4, among them:

(1) a large proportion of anticorrelation between decreasing MDWS trends and increasing CO_2-related component;

(2) only a small fraction of stations with significant contributions from solar forcing or SOI;

(3) some signal from volcanic activity (although it should be interpreted carefully due to the limited number of major eruptions during the 1961–2015 period);

(4) a generally strong and statistically significant NAO signal, although absent in some regions (especially in the Bohemian-Moravian Highlands);

(5) signal from EA/WRP significant especially in the eastern part of the Czech territory;

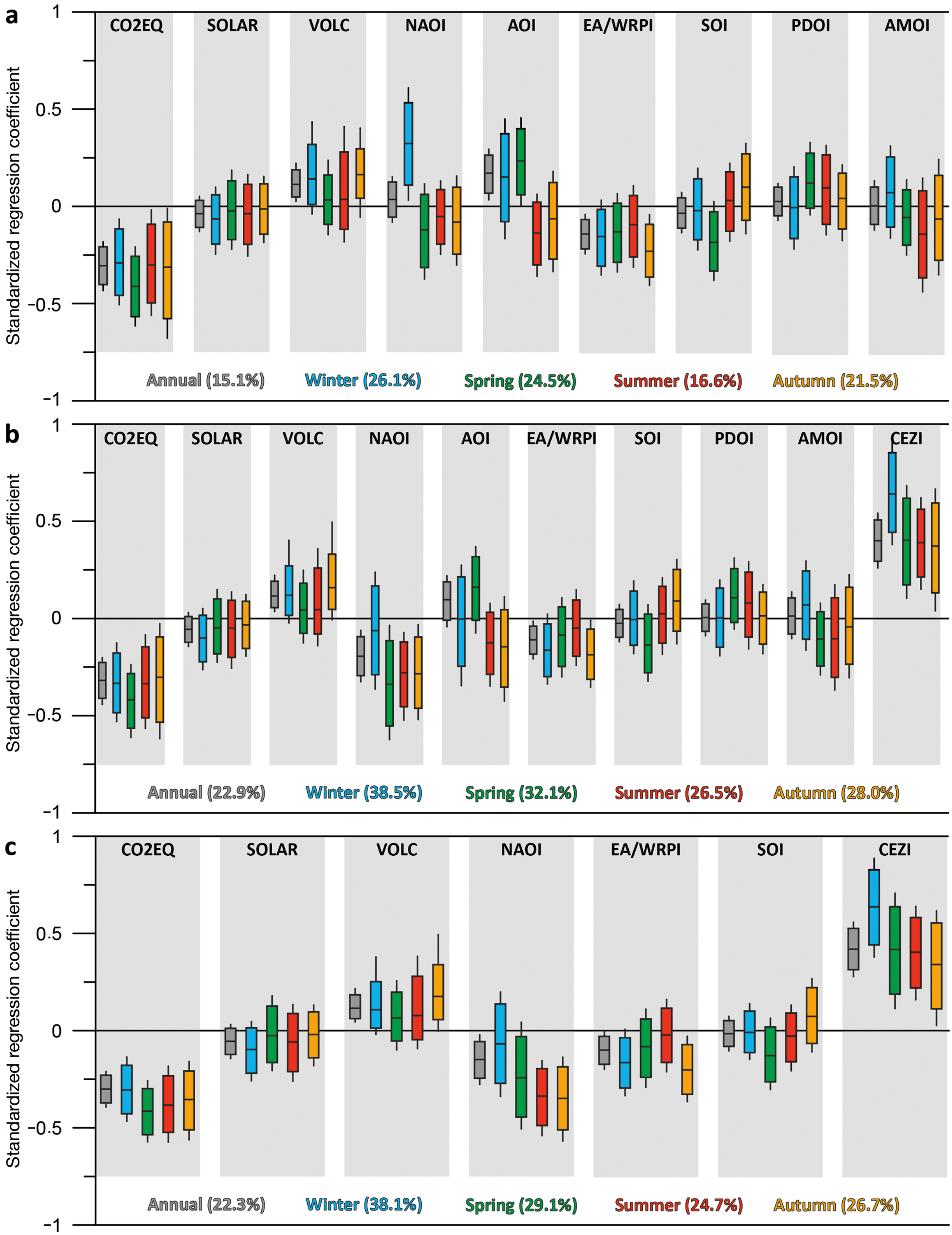

Fig. 3. Standardized regression coefficients resulting from multiple linear regression of Czech mean daily wind speeds (MDWSs) and sets of: (a) 9 explanatory variables of external forcings and climate variability modes, (b) all 10 explanatory variables (the previous predictors + CEZI), (c) the 7 most influential explanatory variables. Columns and whiskers express 95 and 99 % confidence intervals of standardized coefficients, respectively. Annual and seasonal variances of MDWSs explained by the sets of predictors in (a–c) are given as percentages at the bottom of each panel. Variables are defined in Table 2

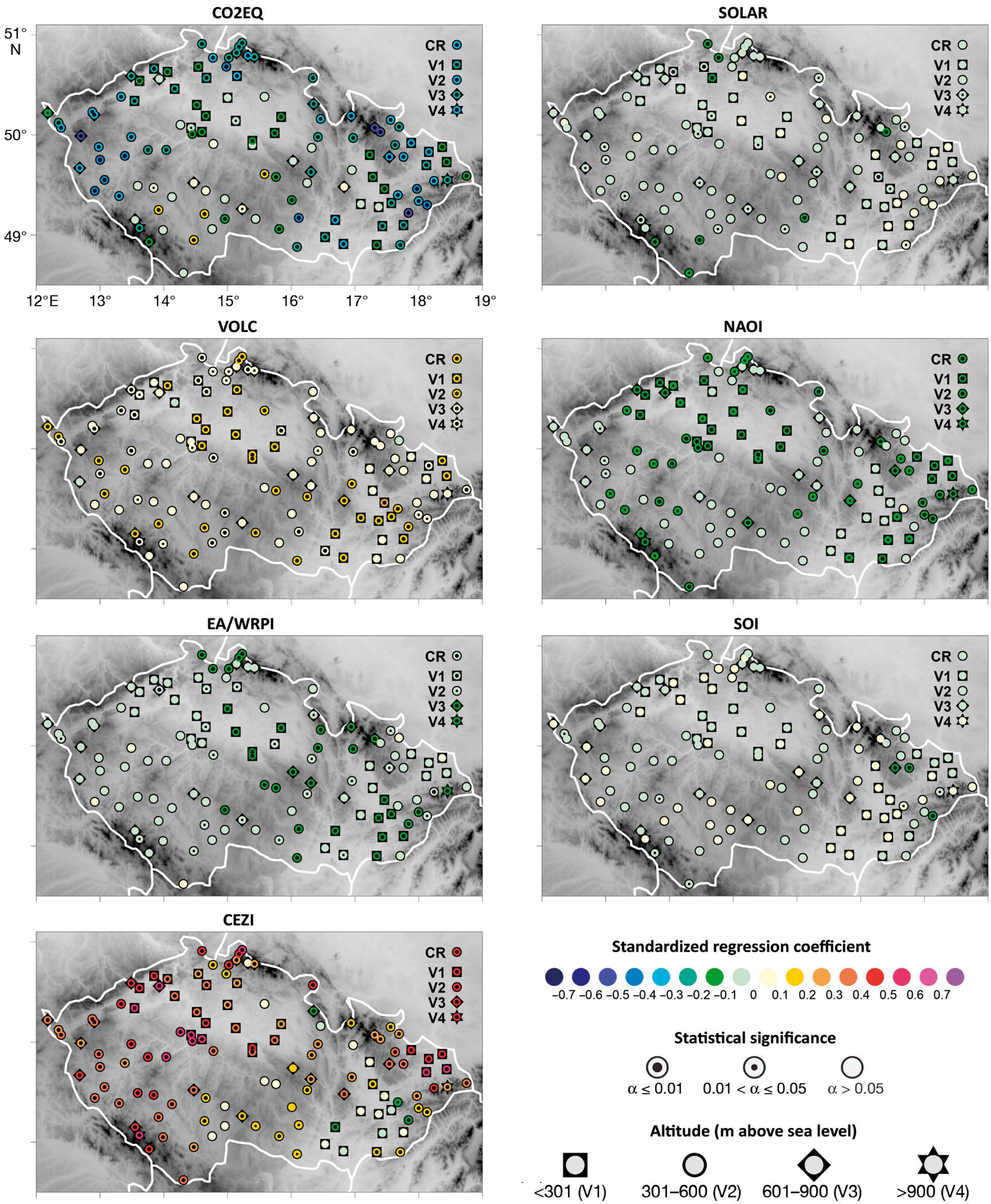

Fig. 4. Geographical distribution of standardized regression coefficients obtained from multiple linear regression approximating the annual mean daily wind speed (MDWS) series at 119 meteorological stations divided into 4 altitudinal intervals (V1–V4) over the Czech Republic (CR) in the period 1961–2015. Variables are defined in Table 2

(6) in similar fashion to the NAO signal, components attributable to CEZI are present at most stations, though somewhat less significant in the southeastern regions.

Because seasonal variations exist for NAOI, EA/WRPI and CEZI influences on MDWSs, Fig. 5 shows standardized regression coefficients for seasonal series from the 119 meteorological stations. In DJF, CEZI is the dominant predictor (explaining most of the variability which would otherwise be ascribed to NAOI if CEZI were not considered), with a smaller contribution from EA/WRPI, especially in the eastern part of the Czech Republic. In other seasons, CEZI is still very influential, but so is NAOI. The influence of EA/WRPI nearly disappears in MAM and JJA, but is quite prominent during SON.

To provide a comparison between the sources of variability in the station-based observational wind data and in their free atmosphere counterparts, regression analysis was also applied to the NCEP/NCAR wind component series at the 850 hPa level. First, a series of wind speeds at the 50° N, 15° E grid point was constructed from the eastward and northward wind components and regressed on a set of 7 explanatory variables identical to the configuration in Fig. 3c (Fig. S1 in the Supplement). While these regression coefficients were largely similar to the MDWS series for the predictors representing internal climate oscillations (NAOI, EA/WRPI, SOI, CEZI), neither anthropogenic nor volcanic forcings were associated with a significant component in the NCEP/NCAR data. In addition to the pointwise analysis of the NCEP/NCAR data, regression analysis was also applied to the spatial fields of zonal and meridional wind speeds at the 850 hPa level. The results, which appear in Fig. 6 for the data without seasonal differentiation and in Figs. S2–S5 in the Supplement for the individual seasons, illustrate the circulation patterns associated with individual modes in the given multivariable configuration of explanatory variables; their implications with reference to Central European wind variability are discussed in Section 5.1.

4.2. Wind-speed RCM simulations

Box plots of annual MDWSs for the Czech Republic for RCP4.5 and RCP8.5 show that uncorrected (i.e. biased) model outputs provide higher values (above 3.5 m s^{-1}) compared with corrected values (slightly above 2.5 m s^{-1}) (Fig. 7). Large differences among biased outputs of individual models are also evident, while after removing model biases (i.e. correcting the model outputs relative to the positions of individual stations in the area of the Czech Republic), the levels of the values are quite different, reflecting measured wind speed at meteorological stations, and the variance between various model values is several times lower.

Turning to individual model biases (Fig. 8), it is clear that these are related to given RCMs rather than to driving GCMs. The highest positive biases occur for the HIRHAM5 and RCA4 regional models, while CLM4-8-17 and RACMO22E models have lower positive biases. ALADIN53 behaves completely differently, as was also the case for other meteorological elements (ALADIN53 exhibited a large negative bias for air temperature, together with RCMs driven by GCM EC-EARTH, and also a notable positive bias for relative humidity in comparison with other models).

4.3. Wind speeds in the climate of the future

Fluctuations in annual MDWSs according to the mean of smoothed values (10 yr Gaussian filter) of all 11 experiments (their ensemble mean) are shown in Fig. 9. Further, the areal mean for the entire Czech Republic is investigated. Biased model values are higher by ca. 1 m s^{-1} compared with bias-corrected values (in the control run, until the 1990s, station values considered without those for which bias-corrected model values were available coincide at 2.5 m s^{-1}).

Figs. 10 & 11 show uncertainty arising out of the use of all 11 Euro-CORDEX simulations, for RCP4.5 and RCP8.5, respectively (see also Fig. S6 in the Supplement). The values have been smoothed by low-pass filter so that values among particular models for individual years are rendered comparable. Generally, the extra-annual variance of wind-speed values is very low, and the uncertainty limits oscillate around the ensemble mean ranging up to only a few (2–3) decimals of m s^{-1} units (compare with uncorrected, biased model outputs in Fig. 7 with much higher variance and uncertainty reaching values beyond 0.5 m s^{-1}).

Station data indicate that trends in MDWSs calculated by means of linear regression are negative and significant (significance level $\alpha = 0.05$) for annual and all seasonal values in the period 1981–2010 (Table 3). Applying corrected model outputs, averaged over the Czech Republic and taking into account the ensemble mean of all 11 simulations, significant negative trends were detected for annual, DJF and JJA series for RCP4.5, and for annual and DJF series for RCP8.5. This means that, for 2 to 3 seasons, observed

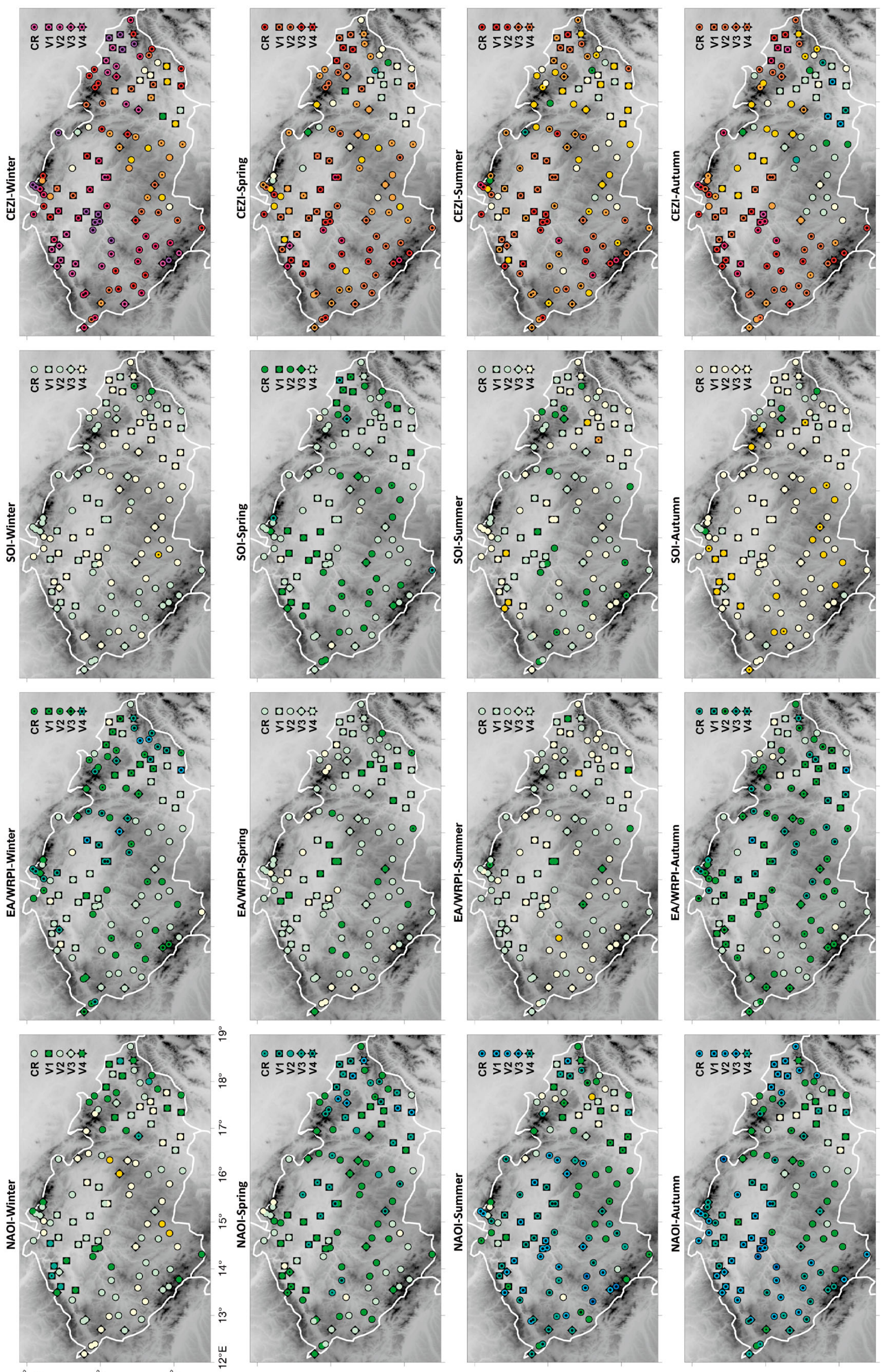

Fig. 5. Geographical distribution of the standardized regression coefficients obtained from multiple linear regression approximating seasonal mean daily wind speed (MDWS) series at 119 meteorological stations divided into 4 altitudinal intervals (see Fig. 4 for symbol and colour keys) over the Czech Republic (CR) in the period 1961–2015 (only NAOI, EA/WRPI, SOI and CEZI are shown of the 7 predictors; predictors defined in Table 2)

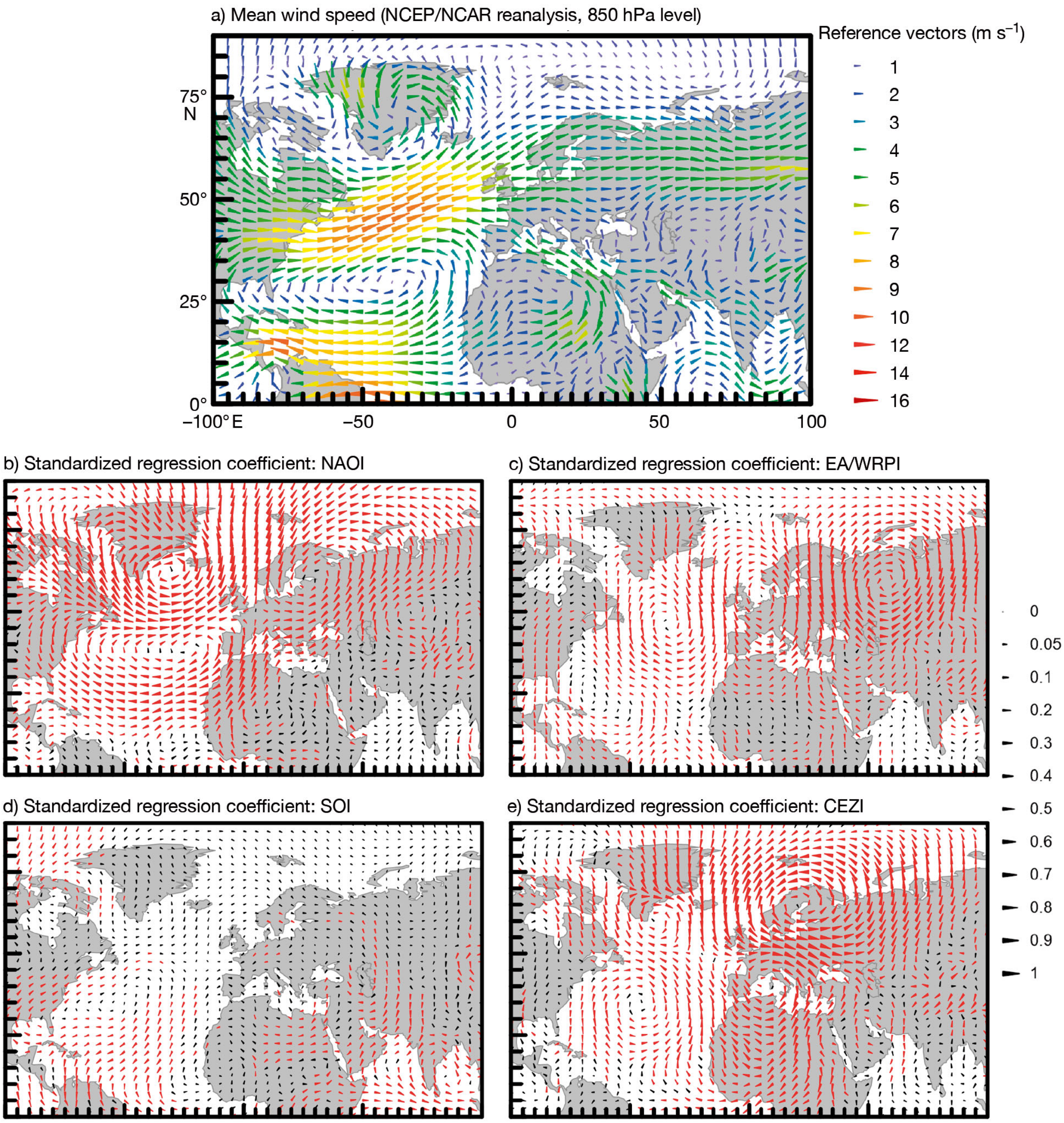

Fig. 6. NCEP/NCAR reanalysis of mean wind field at (a) the 850 hPa level and its components correlated to (b) NAOI, (c) EA/WRPI, (d) SOI and (e) CEZI, expressed in the form of standardized regression coefficients estimated by multiple linear regressions for the set of 7 predictors (defined in Table 2) used in Fig. 3c. Arrows for coefficients with at least 1 wind component (meridional or zonal), statistically significant at the 95% level, appear in red. See Figs. S2–S5 in the Supplement for circulation and response patterns pertaining to individual seasons

significant decreasing trends in MDWSs for both RCPs had always remained overlooked. Taking into account trends calculated for 1981–2100, both RCPs agree in significant negative trends for JJA (–0.08 and –0.16 m s^{-1}) and SON (under –0.04 m s^{-1}), while according to RCP8.5, MDWSs should increase to a significant extent in DJF and MAM (but not more than 0.08 m s^{-1}). This indicates that RCM-simulated changes in MDWSs are negligible.

5. DISCUSSION

5.1. Climate forcings and MDWS series

The results presented herein, as well as prior analyses devoted to observed wind characteristics (Brázdil et al. 2009, 2017a,b), have revealed complex spatiotemporal variability patterns, shaped by the interaction of multiple climate-forming agents, both

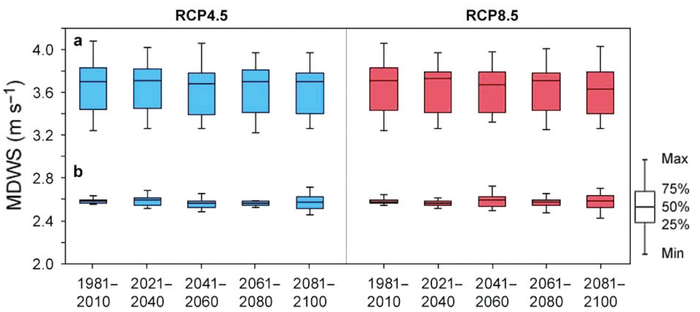

Fig. 7. Comparison of 20 yr periods of (a) uncorrected and (b) corrected model mean daily wind speed (MDWS) for representative concentration pathway RCP4.5 and RCP8.5 scenarios. Box plots show the ranges over all 11 Euro-CORDEX simulations; box plot parameters are defined in the figure

global and local. Multiple linear regression was capable of detecting, separating and quantifying the effects of various large-scale climate drivers of wind speed, formally related to either external or internal influences. The fraction of wind-speed variance explained by regression mappings was typically highest during DJF (approximately 38 % for Czech areal means on a monthly time-scale), and lowest in JJA and SON. This seasonal dependence appeared to be largely attributable to the increased fraction of variance associated with NAOI/CEZI during the cold part of the year (Fig. 3). Its existence conforms with the fact that large-scale climate modes exert more influence on circulation-dominated winter weather conditions, rather than on radiation-influenced summer weather patterns. Overall, CEZI proved to be a more influential predictor than NAOI (cf. Fig. 3b,c). However, comparison of NAOI and CEZI effects in MDWS series (Figs. 3c & 5) also suggests that for seasons other than DJF, NAOI explains a significant part of the variability that CEZI cannot. This behaviour arises out of the definition of CEZI in terms of latitudinal pressure difference, causing components associated with meridional wind directions to be largely disregarded when CEZI is used rather than NAOI.

The roles of NAOI and CEZI as predictors of local atmospheric flow become even more clear in terms of their respective response patterns, shown in Fig. 6 for all-year data and in Figs. S2–S5 for individual seasons. The Central-Europe-focussed CEZI captures much of the zonal flow variability over the Czech Republic, with higher CEZI values associated with stronger westerly winds in all seasons, and thus acceleration of the prevailing westerlies and total wind speeds. These then translate to higher wind speeds at most ground stations (Fig. 4). Positive values of the NAOI predictor are associated with largely easterly perturbations of the local flow in this configuration of predictors, decelerating the mean wind in the free atmosphere as well as at individual stations. Despite the strong relation between NAOI and CEZI (reflected by a mutual correlation of 0.70), both variables should be considered as relevant wind speed predictors and included in the transfer functions when mapping large-scale climate variability onto Central European wind speeds.

The effect of EA/WRP, while smaller in magnitude than the combined NAOI/CEZI influence, was also significant at a number of locations. However, its presence was subject to substantial spatial and seasonal variability, with the strongest links detected for the eastern part of the Czech territory during SON and DJF. The reason for these seasonal differences is clearly apparent from the 850 hPa wind responses in Figs. S2–S5, with a distinct and significant component of meridional wind associated with variations of the EA/WRP phase in DJF and SON, but non-significant responses in MAM and JJA. The wind responses are generally stronger in the eastern part of central Europe, explaining the more prominent influence of EA/WRP in wind series originating from stations located in the eastern part of the Czech Republic.

Aside from NAO and EA/WRP, no other internal climate variability mode tested (SO, AMO, PDO) was found to be associated with a significant component in wind speed, although near-significant responses to SOI or PDOI were indicated during the spring months. It should be noted, however, that the 55 yr long predictand series studied herein were substantially shorter

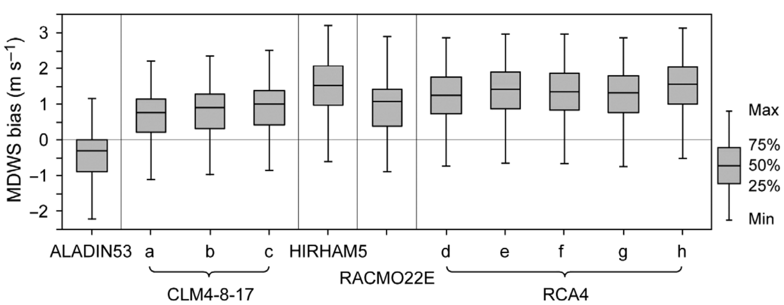

Fig. 8. Bias for mean daily wind speed (MDWS) in individual simulations; control runs over all of the grid points in the Czech Republic (for identification of regional climate models [RCMs], see Table 1). Letters a–h identify driving general circulation models (GCMs) for RCMs (a–c) CLM4-8-17 and (d–h) RCA4, where a: CNRM-CM5, b: EC-EARTH, c: MPI-ESM-LR, d: CNRM-CM5, e: EC-EARTH, f: MPI-ESM-LR, g: HadGEM2-ES, h: IPSL-CM5A-MR. Box plot parameters are defined in the figure

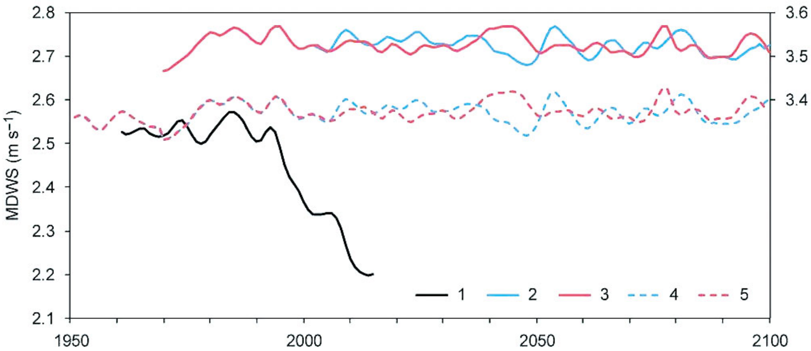

Fig. 9. Fluctuations in annual mean daily wind speed (MDWS) according to mean of smoothed values (10 yr Gaussian filter) of 11 experiments. Line 1: observations, regional climate model (RCM) original model outputs; 2: representative concentration pathway RCP4.5; 3: RCP8.5, RCM outputs corrected for bias; 4: RCP4.5; 5: RCP8.5. Left axis for lines 1, 4 and 5; right axis for lines 2 and 3

ruled out; reference to longer records will be needed for more specific conclusions in the future. This is especially true in light of the borderline significant components in the 850 hPa wind detected at some central European grid points for the DJF and MAM seasons (Figs. S2 & S3) as well as for the year as a whole (Fig. 6).

No direct link between wind speed and solar activity was detected. Nevertheless, the effects of solar activity should not be automatically disregarded in future analyses, particularly in consideration of a recent study by Schwander et al. (2017), analysing the influence of solar variability on the occurrence of weather types in central Europe, and demonstrating a tendency towards fewer days with westerly and west-south-westerly flow over central Europe when solar activity is low. Moreover, mean sea level pressure composite showed a reduced zonal flow with an increase in the mean blocking frequency between Iceland and Scandinavia.

than those employed in most of the prior studies that have addressed attribution analysis of Czech climate records and reported significant links to temperature, precipitation or drought index series (e.g. Brázdil et al. 2012, 2015a,b, Mikšovský et al. 2014). The possibility that Czech wind speeds may be associated with other oscillatory modes cannot therefore be completely

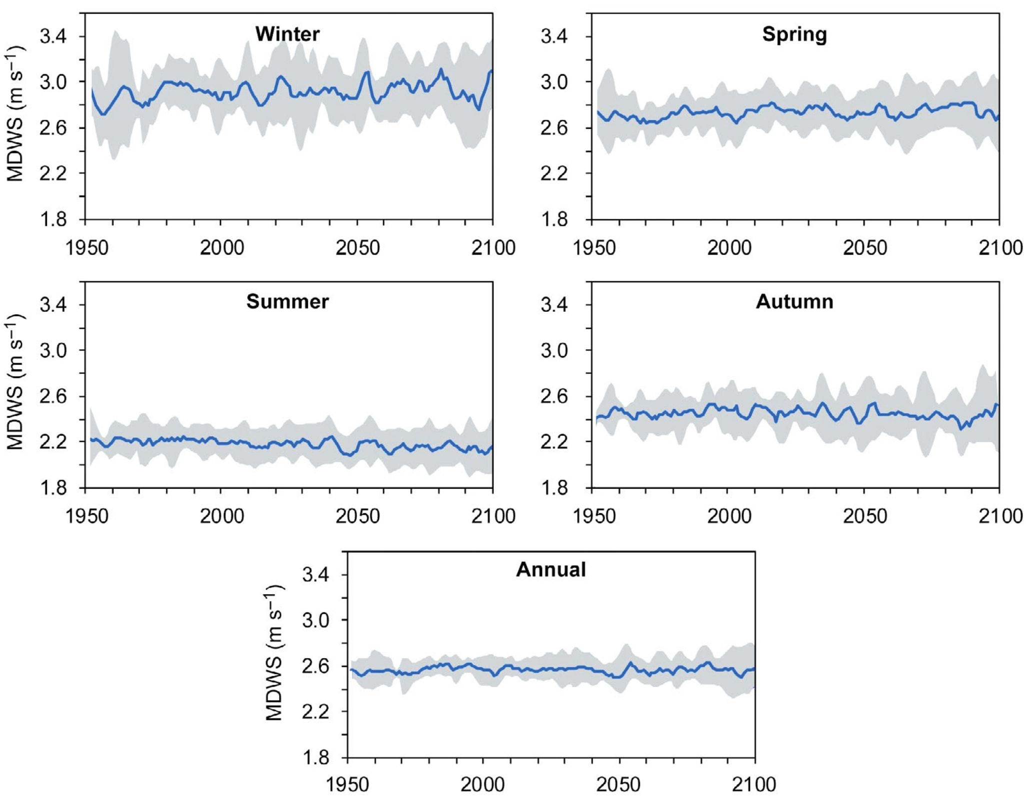

Fig. 10. Fluctuations in seasonal and annual mean daily wind speed (MDWS) for the Czech Republic in the period 1951–2100, under the representative concentration pathway RCP4.5 scenario: ensemble means of all 11 regional climate model (RCM)-corrected experiments (blue) and 90 % intervals of uncertainty (grey). Smoothed by 10 yr Gaussian filter

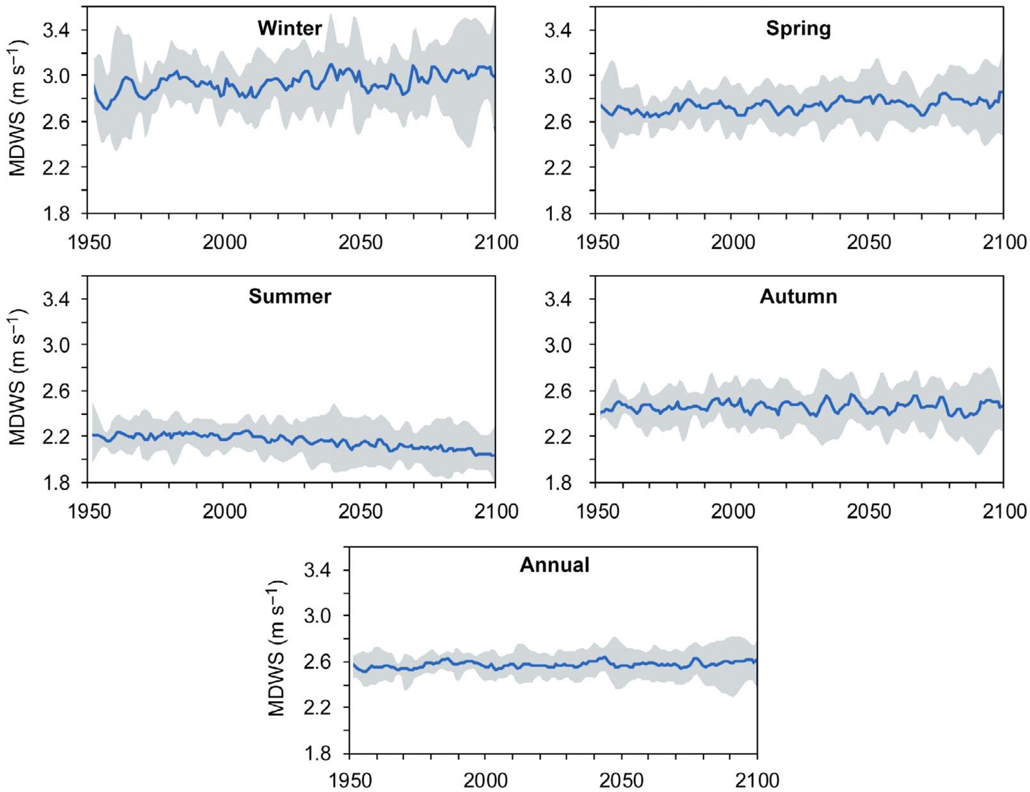

Fig. 11. Fluctuations in seasonal and annual mean daily wind speed (MDWS) for the Czech Republic in the period 1951–2100, under the representative concentration pathway (RCP) 8.5 scenario: ensemble mean of all 11 regional climate model (RCM)-corrected experiments (blue) and 90% intervals of uncertainty (grey). Smoothed by 10 yr Gaussian filter

On the other hand, volcanic activity, the second of the natural forcings considered in this analysis, appears to leave a statistically significant imprint on many local wind-speed series, as well as on their areal means (cf. Fig. 4). While the immediate effect of volcanic activity on Central European climate characteristics is limited and typically statistically non-significant, or merely borderline significant (e.g. Mikšovský et al. 2014, 2016), its distinct effect on global surface temperature (e.g. Canty et al. 2013) demonstrates the prominent role large volcanic eruptions play in establishing pan-planetary atmospheric conditions. If the specific effects of volcanism on the Arctic Oscillation (Stenchikov et al. 2006) are also taken into account, volcanic disturbances of the circulation (and, in turn, wind speeds) in Central Europe are possible. However, the time-frame of this analysis encompassed only a few major volcanic events, with no notable volcanic activity after the Mt. Pinatubo eruption in 1991. The non-significant response to volcanic activity in the NCEP/NCAR 850 hPa wind-speed series (Fig. S1) may indicate that the significant responses in the observational series may be statistical artefacts rather than manifestations of any actual physical link. The effects of volcanism should therefore be considered inconclusive for the data and period studied herein; future use of longer time series may help to achieve more representative results.

Long-term decreasing trends in the wind-speed records are strongly anti-correlated with the series of CO_2-equiva-

Table 3. Mean daily wind speed (MDWS) trends, calculated using linear regression for the Czech Republic from an ensemble of 11 regional climate model (RCM) simulations (smoothed by 10 yr Gaussian filter) for different time intervals. Significant trends ($\alpha = 0.05$) appear in **bold**. RCP: representative concentration pathway

Period	Scenario	MDWS trend (m s^{-1} decade^{-1})				
		Annual	DJF	MAM	JJA	SON
1981–2010	Observations	**−0.136**	**−0.166**	**−0.143**	**−0.086**	**−0.148**
1981–2010	RCP4.5	**−0.009**	**−0.022**	−0.003	**−0.014**	0.005
1981–2010	RCP8.5	**−0.015**	**−0.063**	−0.008	0.001	0.011
1981–2100	RCP4.5	**−0.002**	0.001	**0.002**	**−0.007**	**−0.003**
1981–2100	RCP8.5	0.000	**0.007**	**0.007**	**−0.013**	**−0.002**

lent concentration, the representative of anthropogenic forcing employed in this analysis. The magnitude of the respective standardized regression coefficients is quite similar across all seasons (cf. Fig. 3), and of distinct statistical significance. Despite its formal robustness, this result should not, however, be interpreted as a proof of the causal nature (or physical relevance) of the links revealed. No significant CO_2-correlated component was found in the NCEP/NCAR reanalysis data for the 50° N, 15° E grid point (Fig. S1), suggesting that the trends observed in station data arise out of a different influence, such as changes in local surface character. However, it should also be borne in mind that the reanalysis data do not necessarily produce perfectly homogeneous series, and differences may exist between individual reanalysis products (e.g. Sterl 2004). This may affect the magnitude and significance of the long-term trends detected — see Torralba et al. (2017) for an intercomparison of wind speed trends in several reanalyses during the 1980–2015 period. Since a purely statistical analysis can only identify formal similarities in the data examined, future, more focussed, research will be required to provide a more complete picture of long-term variability attribution, combining different aspects of statistical analysis (potentially involving additional explanatory variables, e.g. related to surface roughness) and outcomes of numerical climate simulations including the potentially relevant surface-related processes.

In this context, a paper by Bichet et al. (2012) may be considered; it employed the ECHAM5 (European Centre Hamburg Model) global climate model to perform sensitivity experiments for the period 1870–2005 and to assess the influence of changing roughness length, aerosol emissions, SST and GHG concentrations on surface wind-speed changes. Despite the dominant influence of increasing roughness length, up to 15% of the magnitude of the land wind-stilling after 1950 could be attributed to climate forcings, particularly increasing aerosol emissions, contributing to wind speed reduction, especially in JJA.

Whereas a decreasing trend is apparent in most multi-decadal Czech wind-speed series, its exact cause remains incompletely explained. Since statistical attribution analysis alone cannot reliably prove, or disprove, any causal link to the explanatory variables (such as anthropogenic forcing), regional climate simulations theoretically constitute more dependable attribution tools, due to their inherently physical nature. However, as the analysis herein has shown, the simulated trends differ substantially from their observed counterparts, not only in terms of magnitude, but even regarding their sign. This discrepancy cannot be fully explained by imperfections in the measured data and their post-processing. A possibly critical role is also played by the limited ability of RCMs (along with their driving global simulations) completely to consider and capture the complexity of the processes in the lowest layers of the atmospheric boundary layer. In the future development of RCMs, related aspects of sub-grid parameterizations therefore need to be substantially upgraded if such simulations are to be used for construction of reliable wind-speed scenarios.

5.2. Uncertainty in wind-speed projections and the European context

Application of 11 RCM simulations to future projections of MDWSs is more challenging than it is for other meteorological variables. While air temperatures are quite well represented by model simulations (with slight bias in the mean), the model biases are quite high for other meteorological elements and quite different among the individual models (e.g. for relative humidity, precipitation totals, number of days with precipitation totals above given thresholds) (cf. Jacob et al. 2014, Kotlarski et al. 2014, Štěpánek et al. 2016). Wind speed is one of the meteorological variables for which model simulations differ to a large extent (as is evident from the data processing carried out for the Czech Republic in Section 4.2).

As shown in Table 3, simulations for both RCPs only partly reproduce signs of observed MDWS trends (disagreement appears in SON and also, in part, in JJA and MAM), while the magnitude of trends is significantly underestimated. These deficiencies may be attributed to surface effects. While increasing surface roughness may be easily observed in real conditions, surface features remain constant in model simulations. This could mean that changes in MDWSs reflected in model simulations according to both RCPs tend to be attributed to changes in the climate system forced by enhanced GHGs. Comparing the model projections of MDWSs for the period 2071–2100 with observed values of MDWSs from 1981–2010, 30 yr means in both RCPs indicate an increase in annual, DJF and MAM values and a decrease in JJA and SON values, higher for RCP8.5 than for RCP4.5 with the exception of SON (annual 0.9 and 0.6%, DJF 4.2 and 2.2%, MAM 2.4 and 1.7, JJA –3.0 and –1.7% and SON –0.3 and –0.6%, respectively).

Rockel & Woth (2007) used 8 RCM simulations for daily maximum and daily mean wind-speed fields from the 'Prediction of Regional scenarios and Uncertainties for Defining European Climate change risk and Effects' (PRUDENCE) project to demonstrate the effects of increasing GHG concentrations on windiness in Europe, using the IPCC SRES A2 scenario to compare the period 2071–2100 with 1961–1990. An overall increase in future wind speeds in DJF and a decrease in SON was obtained, with most of the changes falling in the range of about 1–5%. Similar changes in DJF and SON wind speeds also follow from calculated linear trends in the 1981–2100 period for both RCPs in this paper. However, they are much lower than the negative linear trends for JJA wind speeds (cf. Table 3). Moreover, Rockel & Woth (2007) showed that specific parameterizations are necessary for wind gusts in RCMs. This means that in citing RCM studies, the corresponding model generation should also be taken into account.

Of higher interest than future MDWSs are projections of winter storms or wind gusts. For example, using RCM simulations from the PRUDENCE project and comparing the periods 2071–2100 and 1961–1990 for Europe, Beniston et al. (2007) indicated an increase in extreme wind speeds for winter storms between latitudes 45° and 55° N, more north-westerly than in their reference period. They associated these changes with reductions in mean sea level pressure, leading to more storms in the North Sea, and to an increase in storm surges along adjacent coastal regions. Walter et al. (2006) found differences in modelled (by 3 RCMs) and observed wind speeds of around ±1.0 m s^{-1} for Germany in 1979–1993. Projections of annual wind speeds for 2070–2099 using Regional Model (REMO) 5.0, REMO 5.1 and the MM5 model showed unchanged wind regimes over nearby continental Europe compared with the reference period (1960–1989). Donat et al. (2010b) applied multi-model simulations of RCMs, driven by ERA-40 reanalysis, for the study of spatial patterns of near-surface wind speeds and resulting loss potentials associated with severe winter storms. Kunz et al. (2010) investigated the ability of 3 RCMs, based on REMO and COSMO-CLM (CCLM), to simulate extreme wind speeds in 1971–2000 for Germany. They concluded that all 3 RCMs underestimate the magnitude of gusts by between 10 and 30% for a 10 yr return period. On the other hand, the spatial patterns of gusts were reproduced well. Rauthe et al. (2010) used RCM simulations based on CCLM and REMO to study changes in wind gusts in Germany for the period 2021–2050. Comparing this period with 1971–2000 as a reference, they found a difference between the 2 periods in the range of 6% and −1.5% for wind gusts with a 10 yr return period over northern Germany. Despite non-uniform changes in central and southern Germany, the majority of simulations signal a slight decrease in wind gusts. Nikulin et al. (2011) used an ensemble of RCA3 RCM simulations driven by 6 different GCMs for future projections (2071–2100) of extreme winds in Europe. They identified a wide spread in extreme winds, with a tendency of strengthening to the north of latitude 45° N and weakening south of it, sensitive to the number of simulations in the ensemble. Kjellström et al. (2018) used an ensemble of Euro-CORDEX high-resolution (12.5 km) RCMs to simulate near-surface wind speed for a situation when global mean temperature increases 1.5 and 2°C above pre-industrial conditions. They found a generally inconsistent signal over Europe: decreasing mean wind speed in relatively large areas over the North Atlantic and some parts of the European continent, and increasing trend in some ocean areas in the far north. Regional wind changes showed a strong impact of changes in mean sea level pressure, i.e. in large-scale circulation. The authors argued that 'there is only little (if any) coherence between different simulations and it stands clear that future changes in wind speed are highly uncertain' (Kjellström et al. 2018, p 475). Overall, the results of various existing studies, as well as the results reported herein, suggest that the simulations currently used to describe past and future climate may be inadequate for the capture of local wind trends. A different methodology, involving more potential explanatory factors, is highly desirable if more realistic representations are to be obtained.

6. CONCLUSIONS

We analysed the possible effects of climate forcings and internally induced climate variability on wind-speed series over the current Czech Republic in the period 1961–2015, as well as wind-speed projections for up to the year 2100 based on 11 Euro-CORDEX RCM simulations for climate scenarios RCP4.5 and RCP8.5. The main results are summarised as follows:

(1) Attribution analysis (multiple linear regression) applied to observed wind-speed series indicates significant links to volcanic and anthropogenic forcings; however, these are probably a result of misattribution. No effect of solar forcing was demonstrated.

(2) Large-scale circulation in the European-Atlantic area, expressed by NAOI, and the local latitudinal pressure gradient reflected by the CEZI, have major

effects on the short-term (inter-monthly to inter-annual) temporal variability of wind-speed series. A regionally and seasonally variable effect of EA/WRP was also disclosed.

(3) Large-scale atmospheric flow descriptors from point (2) above may be considered important wind-speed predictors, and included in the transfer functions connecting pressure fields at continental scales to local wind speeds in central Europe.

(4) Validation of wind-speed simulations from 11 Euro-CORDEX RCMs by wind-speed measurement shows that they are overestimated and that it is essential that they have to be corrected for further use. Simulations for RCP4.5 and RCP8.5 express significant decreasing wind-speed trends ('stilling') for annual and winter series, albeit of lower magnitude.

(5) Although projections of wind speeds based on 11 RCM simulations for RCP4.5 and RCP8.5 for the period 1981–2100 indicate significant decreases in summer and autumn wind speeds and an increase in spring series, the anticipated changes achieved only very low values (±0.1–0.2 m s^{-1}).

Future tests, involving more data and the combination of specialized statistical and dynamic models, may be needed to provide more specific conclusions about the causes of long-term variations in wind-speed series. However, obtaining long-term homogeneous wind-speed series remains a critical limiting issue in any such analysis.

Acknowledgements. R.B., P.Z., L.Ř. and P.D. acknowledge the support of the Czech Science Foundation for the execution of project no. 15-11805S. R.B., J.M., P.Š., P.Z., L.Ř. and P.D. also received funding from the Ministry of Education, Youth and Sports of the Czech Republic within the National Sustainability Program I (NPU I), grant number LO1415. P.Š. was supported by the project of the Ministry of Agriculture of the Czech Republic, QJ1610072 System for monitoring and forecast of impacts of agricultural drought. Tony Long (Svinošice) helped with the English. We thank 3 anonymous reviewers and the editor for comments that helped significantly to improve the manuscript.

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Editorial responsibility: Eduardo Zorita, Geesthacht, Germany

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Submitted: January 4, 2018; Accepted: September 28, 2018
Proofs received from author(s): November 2, 2018