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Mapping of extreme wind speed for landscape modelling of the Bohemian Forest, Czech Republic

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Abstract

Extreme wind events are among the most damaging weather-related hazards in the Czech Republic, forestry is heavily affected. In order to successfully run a landscape model dealing with such effects, spatial distribution of extreme wind speed statistics is needed. The presented method suggests using sector-wise wind field calculations together with extreme value statistics fitted at a reference station. A special algorithm is proposed to provide the data in the form expected by the landscape model, i.e. raster data of annual wind speed maxima.

The method is demonstrated on the area of Bohemian Forest that represents one of largest and most compact forested mountains in Central Europe. The reference meteorological station Churáňov is located within the selected domain. Numerical calculations were based on linear model of WAsP Engineering methodology. Observations were cleaned of inhomogeneity and classified into convective and non-convective cases using index CAPE. Due to disjunct sampling of synoptic data, appropriate corrections were applied to the observed extremes. Finally they were fitted with Gumbel distribution. The output of numerical simulation is presented for the windiest direction sector. Another map shows probability that annual extreme exceeds required threshold.

The method offers a tool for generation of spatially variable annual maxima of wind speed. It assumes a small limited model domain containing a reliable wind measurement. We believe that this is typical setup for applications similar to one presented in the paper.

1 Introduction

The Bohemian Forest (Šumava) is a forested mountain range stretching along the Czech-German border with maximum elevation of 1456 m a.s.l. It consists of two national parks that cover 68 000 ha on the Czech side and 24 250 ha on the German side. The area forms a compact landscape dominated by spruce trees. It is generally believed that most of the forest was planted; some of the stands, however, are proved to have developed naturally after a windstorm and a bark beetle outbreak at the end of the 19th century (Svoboda and Wild, 2007). A number of such damaging events also occurred during the last few decades. Windstorm events are – besides severe rain and flooding – the most dangerous and damaging weather phenomena in Europe. In addition to bark beetle outbreaks, extreme wind represents main disturbances affecting the structure and dynamics of spruce-dominated forest, which has been reported in many European mountainous regions (Kulakowski and Bebi, 2004).

In order to address the role of above-mentioned natural disturbances in dynamics of temperate mountain forests, a multidisciplinary project was launched ("The role of disturbances in dynamics of temperate mountain spruce-dominated forests – a landscape simulation model of the Šumava Mts."). The main goal is to modify and calibrate the existing forest landscape model and to concurrently investigate the impact of disturbances on forest dynamics (Scheller et al., 2007; Schumacher et al., 2004) for use over the area of the Bohemian Forest. This paper presents an extreme wind module to be integrated to the landscape model. The module is required as an algorithm giving maximal wind speed at each grid point for each year of the landscape model integration.

The spatial modelling of extreme wind parameters is usually done for large-scale domains using statistical methods and/or regional climate models (Kunz et al., 2010; Donat et al., 2011; Bonazzi et al., 2012). In our case, however, the desired deliverable is fine raster data with parameters of extreme wind speed distribution over the selected limited area. Such fine raster data requires a suitable numerical model able to handle grid resolution of the order of 100 m, and it also demands a reliable reference time series fitted with a proper statistical distribution.

At fine resolution the topographic effects on the extreme wind speed can be evaluated by non-hydrostatic simulation of the most severe wind storms in the reference period (Hofherr and Kunz, 2010). This approach produces good spatial estimates of extreme wind statistics under the assumption that there are enough events in the chosen time period. A different approach is presented by Kalthoff et al. (2003), who used a non-hydrostatic model to calculate a set of wind patterns with two wind direction and five stability classes. In our method, we decided to use a similar approach having 12 wind fields corresponding to the wind direction sectors of the reference observation. We believe that using idealised wind patterns rather than simulating specific events is more robust and less dependent on occurrence of various types of extreme wind situations in the reference period.

Nevertheless, the resolution of the above mentioned studies that used non-hydrostatic models is too coarse for our task. The recent development of non-hydrostatic numerical weather models with a resolution below one kilometre is still complicated and computing costs remain high. Alternatively, a linear model might be employed as it is implemented, for example, in the WAsP Engineering system (Mann et al., 2002). This software is frequently used by the wind engineering community. Therefore we decided to apply the same linear model, despite the fact that it does not account for thermal stratification far from neutral.

Modelling of temporal and spatial behaviour of extreme wind speed is significantly different from that of average wind characteristics. Reference data must be fitted with an extremal statistical distribution prior to use with spatial simulations. A traditional approach of extreme events studies is based on extreme value theory (Král, 2007; Cheng and Yeung, 2002; Pandey et al., 2001). The main assumption is convergence of the distribution of maxima in N value samples to the generalized extreme value (GEV) distribution as the size of the samples increases. Palutikof et al. (1999) presented a good overview of methods used for estimation of extreme value distribution of wind speed. Wind speed is normally expected to follow the Weibull distribution. The block extreme data of variables with Weibull distribution converge to the Gumbel distribution (An and Pandey, 2005), which is a special case of GEV. It is mostly seen in many practical applications and was also applied for the annual maxima in the presented study. Shorter than annual intervals for block maxima should generally not be used as they violate the premise that the samples originate from the same distribution. This fact limits the applicable time series to those with records of definitely more than 10 yr. Extreme wind caused by convective and non-convective events is differently statistically distributed and should be treated separately (Lombardo et al., 2009). In general, the overall impact of both groups of extreme wind events is roughly at the same order throughout the Czech Republic. However, in mountainous regions, non-convective events driven mostly by strong southwest to northwest flow cause significantly more damage.

The aim of this paper is to demonstrate a method of very detailed spatial calculation of annual wind speed maxima. The method consists of numerical modelling of wind fields for various conditions (defined with 12 classes of wind direction) and proper treatment of the available observation (including corrections due to the disjunct sampling, separation of convective and non-convective events and extremal distribution fitting). The second part of the paper deals with the general idea of the method and the setup of numerical model. The processing of wind measurements and the distribution fitting is described in the third part. The fourth part shows the results for the domain of Bohemian Forest and the fifth part concludes and discusses the outcome.

2 Methods and model setup

2.1 Calculation of annual extremes

The final goal of the presented work was to propose an algorithm generating spatial field of annual maxima in the required domain. Due to the desired application, the extremes were produced at 30 m a.g.l.

As a first step, we chose a suitable reference meteorological station located inside the model domain. Observed annual maxima were fit with an extreme value distribution. Based on the theory and reference literature (An and Pandey, 2005), we used traditional Gumbel distribution with cumulative probability function:

$$F(x) = \exp(-\exp(-(x-\mu)/\beta)), \tag{1}$$

where x is the random variable (block maxima of wind speed) and μ and β are distribution parameters (Gumbel, 1958). The distribution was fitted in each wind direction sector, separately for convective and non-convective extremes.

In order to get spatial dimension, the presented method used a linear numerical model to calculate a set of 12 wind fields at requested height above ground. The boundary conditions were defined in such way that wind direction values calculated at the reference station corresponded to the centres of regularly spaced direction sectors. Similar set of calculations was carried out at the reference station at a sensor height of 10 m above ground. All the calculations were bound with 2 above-fitted statistical distributions (for convective and non-convective classes).

In a single time step (year) of the simulation, the algorithm drew random numbers from uniform distribution (0, 1) separately for each sector and for both classes of events. The numbers defined a quantile that was applied from the corresponding distributions which were fitted to the reference meteorological data. We produced annual extremes of wind speed at this single site. Based on the generated annual maxima and simulated wind speed at the reference station, the calculated wind fields were linearly scaled inside each sector and class. Finally, all 24 raster data were overlaid to obtain the maximum at each grid point.

2.2 Linear numerical model

Since the selected area was set in complex terrain of the Bohemian Forest, the available wind speed measurement was strongly affected by local conditions. In order to get the extreme wind speed statistics covering the entire area, it was necessary to apply an appropriate numerical model. In the presented calculation of sector-wise wind fields, we chose the WAsP Engineering methodology (Mann et al., 2002), which is broadly used for estimation of extreme wind speeds. The numerical simulations in the method are based on the linear model LINCOM (Astrup et al., 1997), which was designed for modelling of neutrally stable flow over hilly terrain. Required inputs were raster data of elevation and roughness length parameter. Wind fields were simulated at the generalised wind speed of 20 m s^{-1}, which defined the typical wind speed over smooth flat areas in the domain. The model outputs scaled almost perfectly with the generalized wind speed. The differences were usually at the order of 0.01 m s^{-1}. Therefore, there was no need to calculate more than one wind field for a single direction sector.

2.3 Model domain and topographical data

The project-wide domain defined in the landscape model covers a rectangle of 96 km × 72 km (Fig. 1). For our calculation we chose a model domain of the same extent. However, the horizontal resolution was set to 120 m, double compared to the original value, to prevent the model instability. The essential inputs to the meteorological models were terrain and surface roughness data. In our calculations, we took the digital elevation data from ASTER dataset with original grid size of 60 m. The spatial distribution of the roughness parameter was derived from the European land-cover classification CORINE (Haines-Young and Weber, 2006). The parameter was mapped to individual land-cover classes using values reviewed by Wieringa (1993). This extensive survey considered a large number of documented vertical wind speed profiles over various types of the surface.

3 Observed data and fitting of extreme value distribution

3.1 Wind speed measurements

Surface wind speed is measured at many types of meteorological stations in the Czech Republic. However, our task required quality and temporal coverage that is only found at one professional stations operated by Czech Hydrometeorological Institute (Churáňov, 1118 m a.s.l.). Despite being the best available observation in the region, the time series still had limitations concerning measured wind speed. The station was situated on an open patch; however, the surrounding spruce forest had grown during the measurement period, which clearly impacted the recorded wind speed. This effect was addressed in further data processing.

The site was situated well inside the model domain at the top of a local mountain. Towards east and northeast, the terrain sinks causing slight exposure to wind from those directions. The southern sector is blocked with higher elevation (up to 1219 m a.s.l.). The landscape in the remaining directions was hilly with small changes in elevation.

The extreme wind statistics for Churáňov was calculated from available standard synoptic measurements taken at 10 m a.g.l. First reliable wind data were observed and recorded as early as 1961, but the further analysis also required complementary reanalysis data, which only started in 1979. Therefore, the chosen time period covered 32 yr between 1979 and 2010. The observations were recorded every 3 h until 1981, and were continued with hourly interval afterwards. By definition, the synoptic wind data was distributed as average value of the last ten minutes of a given hour. The effect of disjunct sampling was considered in further statistical processing of the data.

3.2 Separation of convective and non-convective events

As mentioned above, the observations at the reference station had to be classified into two groups distinguishing convective and non-convective events. In further analysis, they were treated separately. Index CAPE (Convective Available Potential Energy) is considered the best tool describing the convective conditions in the atmosphere. The time series of the index was derived from nearest grid point of ERA Interim reanalysis. Since the reanalysis had lower temporal resolution than the synoptic observations (six hours vs. one hour), the maximum was taken from either neighbouring time record.

The threshold value of CAPE used for classification was set at 600 $\mathrm{J\,kg^{-1}}$ because of the following observations. For part of the considered time period, manual weather recordings were available and allowed comparison of CAPE values for observations with and without thunderstorms. As we were interested in high wind speed, only the records exceeding 6 $\mathrm{m\,s^{-1}}$ were compared. This value corresponded to the 90th percentile of the total wind speed data. Figure 2 shows histograms of CAPE for subsection of data between 1994 and 2010 for both weather types. Non-thunderstorm data kept the expected exponential distribution, while the histogram for thunderstorms indicated the maximum number of cases with 20 % frequency at the lowest category (0–100 $\mathrm{J\,kg^{-1}}$) with another peak observed at about 500 $\mathrm{J\,kg^{-1}}$. The large number of thunderstorm events with low CAPE values might have been caused by uncertainties of the reanalysis data and of the manual observation at the station. Nevertheless, we believe that those uncertainties represented mixed events when thunderstorms are part of large scale features. For our purpose we rather had to isolate strong local thunderstorms from the other data. The selected threshold of 600 $\mathrm{J\,kg^{-1}}$, above which the occurrence of convective cases is minimal, seemed to be a good parameter for our classification.

3.3 Corrections to the observed set of annual maxima

The homogeneity of measured wind data is inevitably a very critical issue. Measured wind speed, especially at the extreme values, is affected to a great extent by the measuring technique, surrounding obstacles and terrain roughness. After 1995, a clear inhomogeneity was found in the wind data that could be attributed to the combined effect of changes in surrounding obstacles and growing forest. The ratios of mean wind speed mostly kept between 1.1 and 1.25, with a maximum as high as 1.45 in the 210° sector. Data of the first period were scaled accordingly, as the land-cover data used in the model were produced in 2000 and rather corresponded with the conditions of the later period.

Another bias in the observed annual maxima of wind speed originated from disjunct sampling of the synoptic data. Since we only had one 10 min average within an hour, the available information was limited to one sixth and even less for records with 3 h sampling. A method to correct the annual maxima was developed by Larsen and Mann (2006), who supposed that a time series of wind speed follows the first order Markov chain model. Larsen and Mann (2006) derived the appropriate corrections to the annual maxima from level of autocorrelation of the data.

The autocorrelation of wind speed data at Churáňov yielded 0.902 and 0.815 at hourly and at 3 h intervals, respectively. These values indicted that the wind data did not completely fit the Markov chain model and suggested that better information for the correction might be obtained from continually sampled data. However, only the last five years were covered by continuous data with 15 min sampling interval and would not provide representative results. We therefore decided to apply the values derived from synoptic data, as the effect of extreme wind speed would be calibrated in the landscape model. We rather aimed for the spatial distribution of extremes than precise correction of disjunct sampling. Following the suggested procedure of Larsen and Mann (2006), the expected attenuation factor of observed extremes reached 0.938 and 0.881 at hourly and at 3 h intervals, respectively.

3.4 Distribution fitting

As noted earlier, we decided to base our method on the Gumbel distribution. The corrected annual maxima of wind speed were fitted in each sector for both previously defined groups of observations using maximum likelihood (ML) algorithm. The results for the wind direction sectors with highest and lowest mean wind speed are displayed in Fig. 3. The convective data yielded lower values, but the difference became smaller towards very high return periods. Figure 4 demonstrates the sector-wise distribution of derived extremes with 50, 200 and 1000 yr return periods.

Additionally, we checked how precisely the extreme data followed the Gumbel distribution. We used the Anderson–Darling test, which gives more weight to the tail of the distribution. In our extreme data analysis, it was therefore preferred over the standard Kolmogorov–Smirnov test.

The test results were similar for both event classes. Five sectors passed the test (the hypothesis that the data come from the tested distribution was not rejected) at the significance level of 5 %, while eight or nine sectors passed at the significance level 1 %. The remaining values did not exceed the latter critical value (1 %) to big extent and mostly appeared in less frequent wind direction sectors. The not-perfect outcome of the test may have resulted from using sector-wise maxima, as the individual sectors contained less extreme events than the entire dataset. However, this sector-wise approach was necessary for proper representation of spatial distribution of extreme wind speed.

In order to explore a more general form of the statistical model, we also fitted the data with the Generalized Extreme Value (GEV) distribution. The Gumbel distribution is a subset of the GEV distribution and it is normally possible to compare its suitability using ML ratio test (Wilks, 2011). In the presented dataset, one sector of non-convective group and four sectors of convective group contained data for which the GEV distribution was preferred over the Gumbel distribution at significance level of 5 %. Those cases mostly corresponded to the sectors with poor results of the Anderson–Darling test for the Gumbel distribution. We found that the outcome of both tests was clearly affected by the presence or absence of data in the tail part of the distribution, which did not show any structure regarding to the wind direction. Occasionally, the fit of the GEV distribution produced only limited right tail, meaning there would not be any extreme values generated above that limit. Moreover, the quantities with parent Weibul distribution theoretically produced block maxima following the Gumbel distribution. We therefore suggest using Gumbel distribution in the required algorithm.

4 Results

4.1 Numerical simulations of wind fields

Wind speed fields were calculated for each of 12 direction sectors at generalised wind speed of 20 $\mathrm{m\,s^{-1}}$. The presented version shows results at 30 m above ground, as this corresponded to the intended use in the landscape model. Our results revealed that terrain and roughness affected simulated wind speed. This impact was especially apparent in the case of the windiest western sector as documented in Fig. 5. The wind speed above the flat terrain was few $\mathrm{m\,s^{-1}}$ below the reference wind speed, as the

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overall roughness in the domain was higher than the model reference. In contrast, at the most exposed ridges wind speed reached between 25 and 35 $\mathrm{m\,s^{-1}}$ due to the terrain effects. The structure of results for the other wind direction sectors was similar to the western sector. However, the areas affected with highest wind speed moved as the wind direction changed.

The chosen numerical model was also evaluated at the reference station at appropriate anemometer height. Results are shown in Fig. 6. The differences between neighbouring sectors did not exceed few $\mathrm{m\,s^{-1}}$ and reflected the exposition of the meteorological station. Each simulated wind field was linked with the corresponding value calculated at the reference station to be able to proceed with the above-described method.

4.2 Probability of extreme wind speed and sensitivity to wind direction

For purpose of demonstration and visualisation of the output of the final algorithm in the landscape model, the probability of wind speed exceeding 30 $\mathrm{m\,s^{-1}}$ was calculated for each grid point at selected height 30 m above ground. The almost perfect linear scaling of the numerical model allowed us to calculate such probability by scaling the parameters of original distribution at the reference site. The single grid point had 24 probability values corresponding to the original distributions. As the distributions in the direction sectors were considered to represent independent processes, the total probability could be easily obtained from the individual values.

Figure 7 shows the corresponding results in the map. Values at the most exposed ridges often reached more than 10 % and dropped to under 1 % outside those areas.

The overall probability map depicts the most affected areas, but does not demonstrate how the orientation of exposed sites affected the generation of wind speed maxima. We therefore chose two sites with different orientation and produced the 50 yr time series to show the benefits of using sector-wise approach. In the Fig. 8, both time series are annotated with the sector and corresponding quantile values responsible for the simulated event. Site A faced 210° azimuth, site B was oriented towards 300°.

Events from sectors corresponding to or neighboring the site orientation clearly impacted the generated maxima of A and B, however events from sector of 210° did not affect site B and vice versa.

5 Conclusions and discussion

The main goal of the presented work was to produce estimates of spatial distribution of extreme wind speed parameters over a domain of the Bohemian Forest. Parameters were used to trigger extreme wind events in a forest landscape model. The suggested method combined spatial calculations using a linear model of the WAsP Engineering system and reference observations fitted with extremal statistical distribution. Extreme wind speed maps were produced for each sector of generalized wind direction at 30 m above ground level to fit the original purpose. The calculations were done at generalised wind speed set to $20\,\mathrm{m\,s^{-1}}$.

We chose the synoptic meteorological station Churáňov as reference measurement, which is located within the project domain. Apparent inhomogeneity was removed from the time series and the corrections for disjunct sampling were applied. Observations were also classified to convective and non-convective cases using index CAPE, values of the index were derived from the reanalysis ERA Interim. Both groups of observations were fitted with typically used Gumbel distribution in each direction sector, which normally best follows the block maxima of random variables. In the presented algorithm, the distributions were evaluated each year in the simulation and the resulting values are scaled using corresponding simulated wind fields. Results of all sectors were overlaid to generate the final layer of annual wind speed maxima.

To sum up, the presented method was able to produce reasonable estimate of spatial distribution of extreme wind speed over the selected domain. The numerical model, however, was linear and assumed a neutrally stable boundary layer. This assumption is generally fulfilled, but some specific events of extreme wind speed can be accompanied by more complicated thermal stratification of atmosphere, e.g. the strong katabatic wind (bora). To include those situations in the calculations, we would have had to use non-hydrostatic modelling and much more detailed classification of events and reference observations (e.g. according to the thermal stratification). However, due to the limits on horizontal resolution, the non-hydrostatic model would need to be combined with another method in order to get required detailed output. Such possibilities will be explored in further research in the project.

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Fig. 1. Position of the model domain within the area of Central Europe.

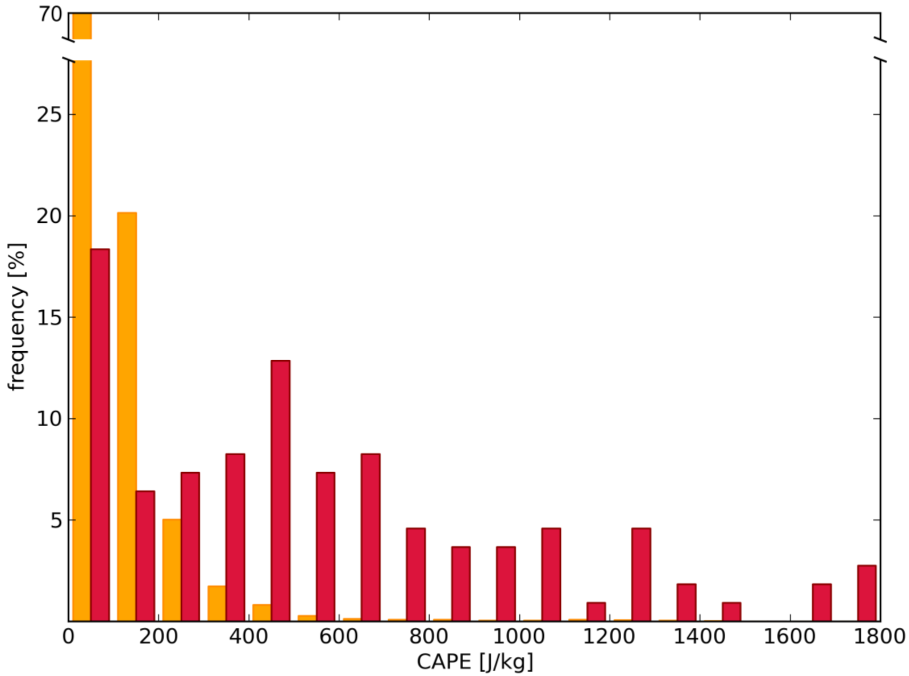

Fig. 2. Histogram of index CAPE for thunderstorm (red) and non-thunderstorm (orange) cases at the meteorological station Churáňov in the period 1994–2010. The values of CAPE are extracted from ERA Interim reanalysis archive at the nearest grid point.

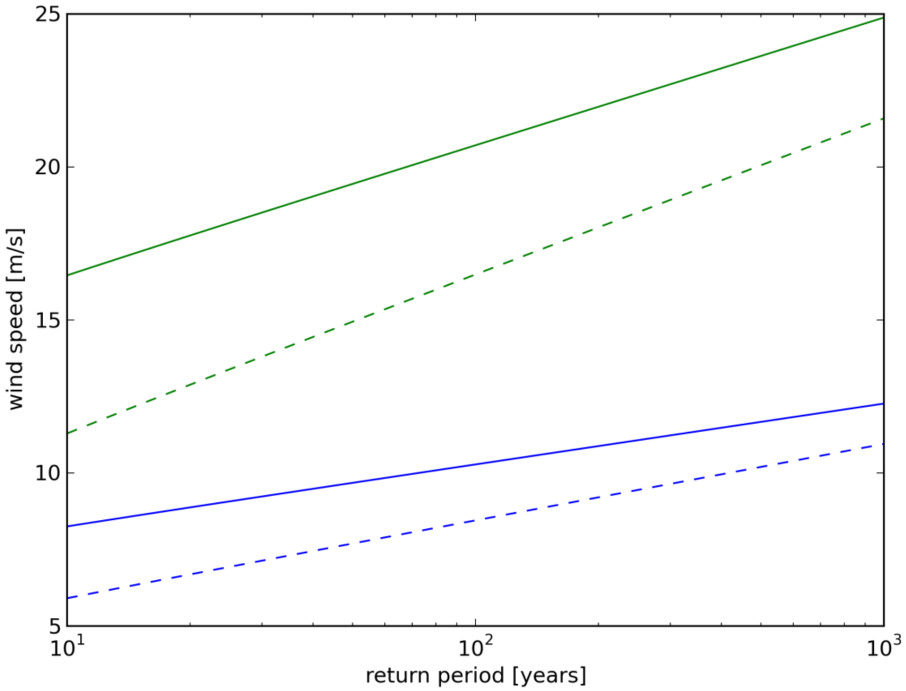

Fig. 3. Gumbel distribution fitted to the annual extremes of wind speed at the meteorological station Churáňov in 1979–2010. The green lines show the wind direction sector of 270° with the highest mean wind speed, while blue lines show the sector with lowest mean wind speed centred at 60°. Full lines represent the distributions of non-convective extremes; dashed lines the distributions connected with convective events.

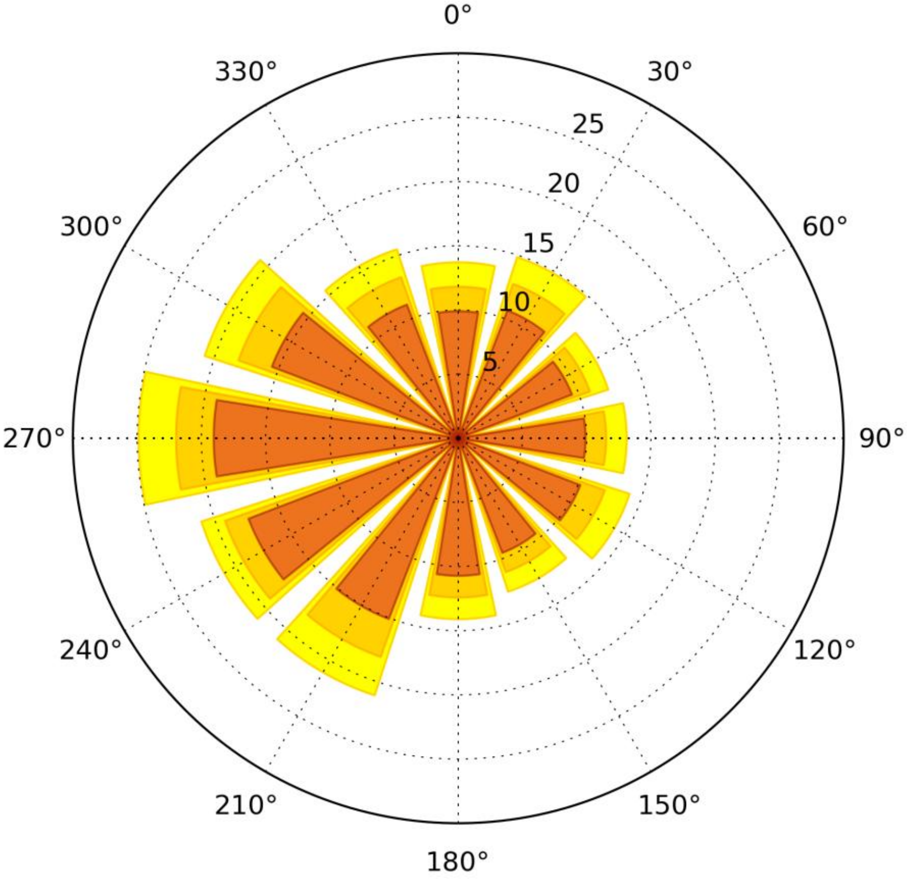

Fig. 4. Annual non-convective extreme of mean wind speed (in $\mathrm{m\,s^{-1}}$) with 50, 200 and 1000 yr return period in 12 wind direction sectors.

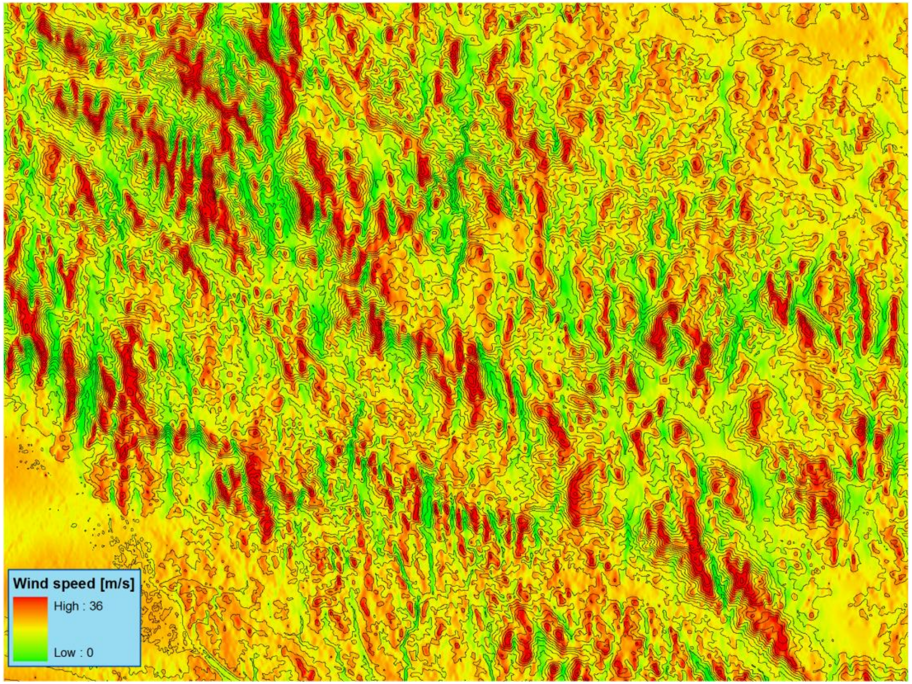

Fig. 5. Wind field calculated for the most frequent 270° wind direction at generalised wind speed of $20\,\mathrm{m\,s^{-1}}$. The calculation is done by linear model of WAsP Engineering 3.

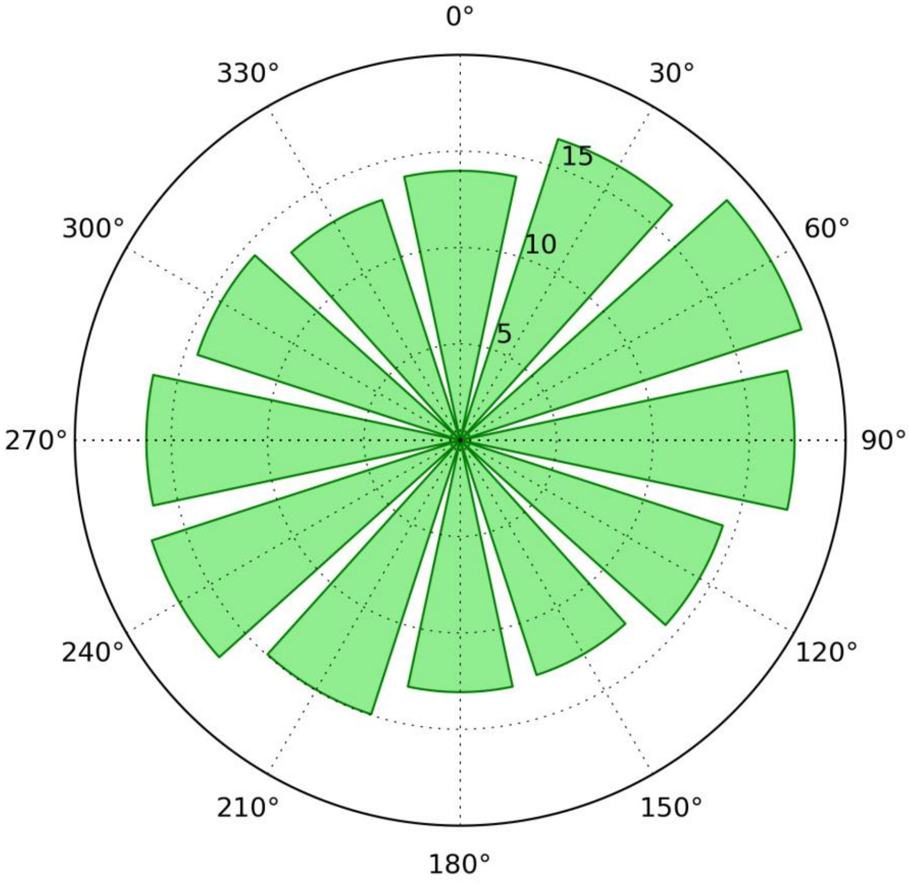

Fig. 6. The wind speed [$\mathrm{m\,s^{-1}}$] calculated at reference site in 12 wind direction sectors using generalised wind speed of $20\,\mathrm{m\,s^{-1}}$.

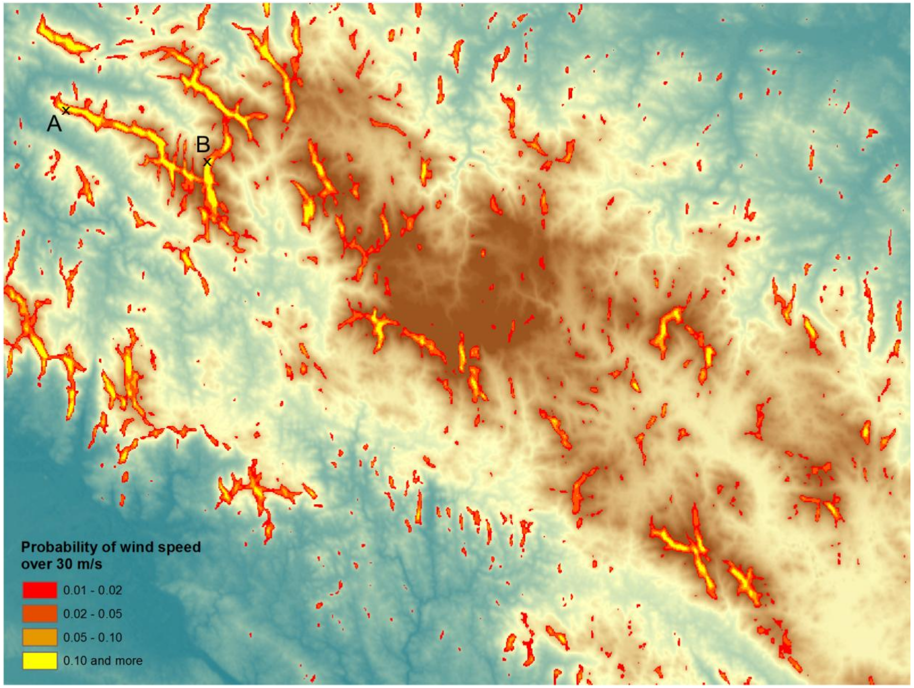

Fig. 7. The probability of occurrence of annual wind speed maxima exceeding 30 m s^{-1} at 30 m a.g.l. in the suggested algorithm. Letters A and B denote the locations discussed in the text.

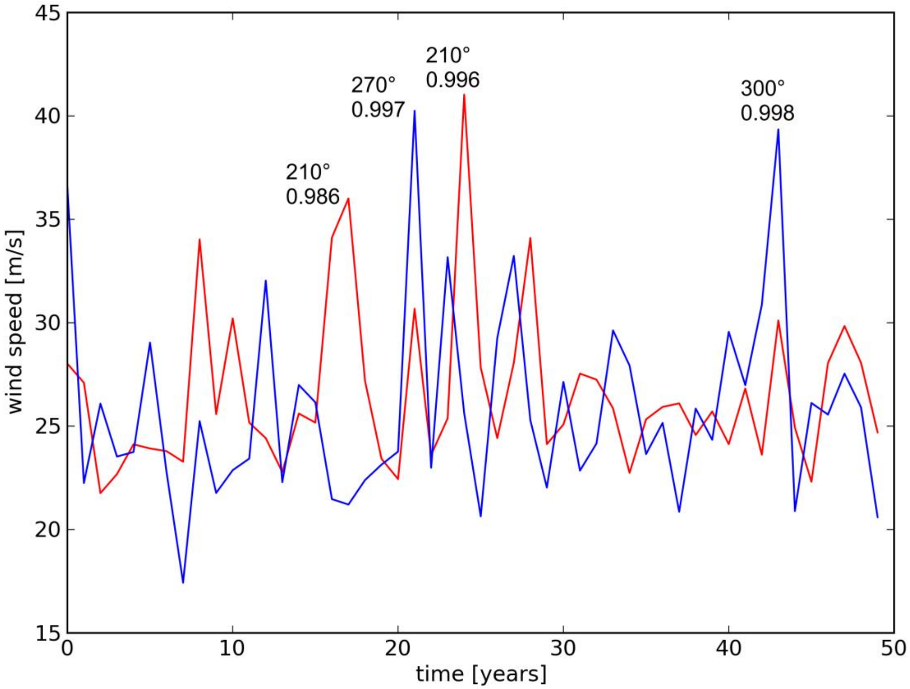

Fig. 8. 50 yr time series of annual maxima of wind speed at 30 m a.g.l. generated for locations A (red) and B (blue). The highest peaks are annotated with the sector and corresponding quantile value responsible for the simulated event.