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 68000 ha on the Czech side and 24250 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 speed causes 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 the 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 on the area of the Bohemian Forest and to investigate the impact of disturbances on forest dynamics (Scheller et al., 2007; Schumacher et al., 2004). This paper presents a method for generation of extreme wind speed to be integrated in the landscape model. The method is expected to produce annual maximum of wind speed at each grid point in 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 the presented work, however, the desired deliverable is fine raster data of annual maxima of wind speed generated over the selected limited area. Such detail requires a suitable numerical model able to handle grid resolution of the order of 100 m. Furthermore, a reliable reference time series is needed in the domain.

Better spatial resolution usually achieved by non-hydrostatic simulation, when the most severe wind storms in the reference period are simulated (Hofherr and Kunz, 2010). The topographic effects on the extreme wind speed are evaluated better than in climate models and good spatial estimates of extreme wind statistics are produced 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 predefined wind patterns with two wind direction and five stability classes. In the presented method, a similar approach is used with wind fields computed for each wind direction sector of the reference observation.

Nevertheless, the resolution of the non-hydrostatic models is too coarse for use in the landscape model. 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. The presented method applies the same linear model, despite the fact that it only assumes thermal stratification close to neutral.

Modelling of temporal and spatial behaviour of extreme wind speed is significantly different from using average wind characteristics. Reference data must be fitted with an extremal statistical distribution prior to use in spatial simulations. A traditional approach of extreme event research 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 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 years. 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 detailed spatial calculation of annual wind speed maxima. The method consists of numerical modelling of wind fields for various conditions (defined with reference wind direction) and proper treatment of the reference measurements (including corrections due to the disjunct sampling, separation of convective and non-convective events and extremal distribution fitting). The basic methodology is presented in the second section of the paper. The third section deals with the processing of wind measurements and the distribution fitting. The setup of the numerical model is described in the fourth part. The fifth part shows the results for the domain of Bohemian Forest and the sixth part contains conclusions and discussion.

2 Basic methodology

The goal of the presented work was to propose a method that generates detailed spatial field of annual maxima of wind speed in given domain. Due to the application in forestry, the extremes were required at 30 m above ground. The proposed method is schemed on the flowchart in Figure 1. It consists of two parts – the initial computation, which needs to be done only once, and the generation of annual maxima, which can be repeated as necessary.

As a first step of the initial computation, a suitable reference meteorological station was chosen inside the area of interest. The wind data were checked, corrected and split in two convective categories (CC) separating convective and non-convective conditions. Annual maxima were extracted in each CC and wind direction sector (WD) and fit with an extreme value distribution. The block maxima of quantities with parent Weibull distribution, such as the wind speed, normally follow the Gumbel distribution. Based on the theory and reference literature (An and Pandey, 2005), the Gumbel distribution was applied with cumulative probability function:

$$F(x) = \exp (-\exp (-(x - \mu)/\beta)), \quad (1)$$

where x is the random variable (block maxima of wind speed) and μ and β are distribution parameters (Gumbel, 1958).

In second step of the initial computation, a domain for a linear numerical model was chosen and wind field was computed for each WD at the height of anemometer at the reference station (10 m a.g.l.) and at the height required for output (30 m a.g.l.). The numerical model was supplied with such boundary conditions that wind direction at position of the reference station corresponded to the centres of WD sectors. The wind fields were computed at the generalised wind speed of 20 m/s defining the typical wind speed over smooth flat areas in the domain. It was not necessary to calculate more than one wind field for a single direction sector, because the outputs of linear model scaled perfectly with the generalized wind speed with differences under 0.1 m/s. The reference wind speed u_{ref} was extracted for each WD from 10-meter wind field at the position of the reference station.

The final part of the proposed method was intended to be integrated in the landscape model and focused on generation of annual maxima at each grid point of the domain. First a random number *q* is generated from uniform distribution (0, 1) for each combination of CC and WD. The annual maximum of wind speed u_{max} is calculated for each category as quantile *q* of corresponding Gumbel distribution. Only the higher value of convective and non-convective u_{max} was kept in each WD. The computed wind fields were linearly scaled using $R= u_{max} / u_{ref}$ in each category of WD. Finally, the results for all WD were overlaid and maximum was calculated at each grid point.

3 Reference wind speed measurements

3.1 Meteorological station and observed wind data

The reference meteorological station should provide data with high quality and long enough temporal coverage. In the area of study, only one station met the requirements. It is located on the top of a local mountain – Churáňov – at 1118 m a.s.l. and operated by the Czech Hydrometeorological Institute. Despite the high quality and the length of observation, the time series has limitations concerning measured wind speed. The station was originally 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 basic analysis of the measured data (Figure 2) shows that the most frequent wind direction observed at Churáňov ranged from southwest to west. Similarly, the highest wind speed was found in southwestern and western sector as demonstrated by the values of 50th, 95th and 99th percentile. A small secondary maximum was identified in northeastern sector.

The observed wind rose results from combination of the general circulation pattern and the effects of orography. The regional wind is generally most frequent and strongest from west, northwest and southwest. The local orographic effects, however, favour wind from southwest and northeast perpendicular to the main mountain ridge and deform the regional wind rose. South wind is further inhibited as blocked by local terrain (up to 1219 m a.s.l.).

The extreme wind dataset for Churáňov was derived from standard synoptic measurements at 10 m a.g.l. The reliable time series of wind speed and direction started as early as 1961, but the further analysis required corresponding reanalysis data, which were available earliest in 1979. The part of time series was therefore used from 1979 to 2010. The observations were recorded every 3 hours until 1981 and with hourly interval afterwards. By definition, the synoptic wind data are sampled as average of 10-minute period prior to the given hour. The effect of such disjunct sampling was considered in further statistical processing of the data.

3.2 Corrections to observed wind data and annual maxima

The homogeneity of any wind speed measurements is very critical issue. The wind speed, especially the extreme values, is strongly affected by measuring technique, surrounding obstacles and terrain roughness. The analysis of wind speed observed at Churáňov revealed a clear inhomogeneity that could be attributed to the combined effect of changes in surrounding obstacles and growing forest. The ratios of mean wind speed observed before and after the year 1995 ranged between 1.1 and 1.25 for most of wind directions, but reached as high as 1.45 in the 210° sector. The wind speed in the period before the year 1995 was scaled using ratio of corresponding wind direction sector. The land-cover data used for modelling were produced in 2000 and reflect the conditions of the later period.

Another bias appeared in the annual maxima calculated from observed wind speed. It originated from disjunct sampling of the synoptic data. Since we only had one 10-minute average within an hour, the available information was limited to one sixth and even less for records with 3-hour 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-hour 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, the continuous data with 15-minute sampling were only available for the last five years and would not have provided representative results. The corrections were calculated from obtained autocorrelation levels assuming the Markov chain process. 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-hour intervals, respectively.

3.3 Separation of convective and non-convective events

To separate the wind speed extremes of convective and non-convective events, the observations at the reference station were separated into two categories using the index CAPE (Convective Available Potential Energy). CAPE is considered to be the best tool describing the convective conditions in the atmosphere. The time series of CAPE at position of the reference station was extracted from the nearest grid point of ERA Interim reanalysis. Temporal resolution of the reanalysis (six hours) was significantly coarser compared to the hourly synoptic observations. The observations not corresponding to ERA Interim data were mapped to the maximum of neighbouring records of CAPE.

The threshold value of CAPE used for separation was set to 600 J/kg because of the following observations. Manual weather recordings were available in part of the considered time period, which contained information on thunderstorm occurrence. Based on those data the CAPE values were compared for observations with and without thunderstorms. Due to the focus on extreme wind speed, only the records exceeding 6 m/s were compared. This value corresponded to the 90th percentile of the observed wind speed distribution. Figure 3 shows histograms of CAPE for subsection of data between 1994 and 2010 for both weather types. Non-thunderstorm data followed the expected exponential distribution, while the histogram for thunderstorm data indicated more complex distribution with the maximum at the lowest category (0-100 J/kg) and another peak observed at about 500 J/kg. 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 believed that those uncertainties represented mixed events when thunderstorms were part of large scale features. On the other hand, the crucial function of the separation was isolation of strong local thunderstorms from the other data. The occurrence of non-thunderstorm records was minimal above the selected threshold of 600 J/kg, so that this value fitted well the purpose of the separation.

3.4 Distribution fitting

In the proposed method, the corrected annual maxima of wind speed were fitted with the Gumbel distribution in each sector and each convective category. The distribution parameters were calculated using maximum likelihood (ML) algorithm. The results for the wind direction sectors with highest and lowest mean wind speed are displayed in Figure 4. The convective data yielded lower values, but they converge to the parameters for non-convective data towards very high return periods. Figure 5 demonstrates the sector-wise distribution of derived extremes with 50-, 200- and 1000-year return periods.

Additionally, a statistical test was calculated how precisely the extreme data followed the Gumbel distribution. The Anderson-Darling test was preferred over the standard Kolmogorov-Smirnov test, as it gives more weight to the tail of the distribution.

The test results were similar for both convection categories. 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 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, the sector-wise approach was necessary for proper representation of spatial distribution of extreme wind speed.

In order to explore more general form of the statistical model, the data were fitted with the Generalized Extreme Value (GEV) distribution. The Gumbel distribution is a subset of the GEV distribution and it is possible to compare its suitability using ML ratio test (Wilks, 2011). In ML ratio test of the presented dataset, only one sector of non-convective category and four sectors of convective category indicated that the GEV distribution was preferred over the Gumbel distribution (significance level was 5%). Those cases mostly corresponded to the sectors with poor results of the Anderson-Darling test for the Gumbel distribution. 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 fitted GEV distribution had limited right tail, so that no extreme values would have been generated above that limit. The Gumbel distribution was therefore preferred in the presented method.

4 Numerical computation in domain of Bohemian Forest

4.1 Model setup and topographical data

Due to complex terrain of the Bohemian Forest, the reference wind speed measurements were strongly affected by local conditions. In order to generalise the extreme wind speed statistics to the entire area, it was necessary to apply an appropriate numerical model. In the presented method, the wind fields were computed using the linear model LINCOM (Astrup et al., 1997), which was designed for modelling of neutrally stable flow over hilly terrain. The model is part of the WAsP Engineering (Mann et al., 2002) broadly used for estimation of extreme wind speed (Rathmann et al., 1999; Larsen and Mann, 2009).

The model domain for the computation of wind fields covered a rectangle of 96x72 km (Figure 6) and corresponded to the domain defined in the landscape model. However, the horizontal resolution of the domain was decreased from 60 to 120 m to prevent numerical instability. The inputs required to run the model are raster data of elevation and roughness length parameter. The digital terrain was extracted from ASTER dataset with original grid step 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 study considered a large number of documented vertical wind speed profiles over various types of the surface.

4.2 Computation of wind fields

According to the basic methodology, the model was initialized with generalised wind speed of 20 m/s wind speed and 12 wind directions. The wind fields were computed at 10 and 30 m above ground. The effect of terrain and roughness on simulated wind speed in the case of the windiest western sector is displayed in Figure 7. The wind speed above the flat terrain was few m/s below the generalized wind speed, as the overall roughness in the domain was higher than the model reference. In contrast, wind speed reached between 25 and 35 m/s at the most exposed ridges 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 model wind speed at the reference station was sampled from the wind fields computed at 10 m above ground. The differences between neighbouring wind direction sectors did not exceed few m/s and reflected the exposition of the meteorological station. Each wind field simulated at 30 m above ground was linked with the corresponding value at 10 m at the reference station to be able to scale the wind fields with generated annual extremes.

5 Final results

5.1 Probability map of extreme wind speed and sensitivity to wind direction

The final result of the presented work was a generator of annual maxima of wind speed integrated into the landscape model. In a visual form, the result is best demonstrated by a probability map of occurrence of annual maximum of wind speed over certain value. The threshold was set to 30 m/s, as the probability of annual maxima exceeding this value was only notable at the most exposed parts of the domain. Since the wind fields were computed by linear model, they could be scaled linearly and the parameters of Gumbel distributions could be directly calculated from the parameters fitted at the reference site. At a single grid point, the 24 probability distributions were considered to represent independent processes, so that the total probability of exceedance of 30 m/s could be easily obtained. Figure 8 shows the corresponding results in the map. The probability at the most exposed ridges often reached more than 10%, but it did not exceed 1% otherwise.

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. Two grid points of the domain with different orientation was chosen and 50-year time series of annual maxima was generated using same set of random numbers. In Figure 9, 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°. The result showed that events generated at sectors corresponding to the site orientation clearly impacted the resulting annual maxima.

5.2 Comparison with observed forest disturbances

Since the suitable meteorological measurements were only available at one point, direct verification of calculated wind speed extremes over the selected domain was not possible.

There was an option, however, to compare the results with forest disturbances observed after a major windstorm. A suitable dataset was collected by crew of the National Park Šumava after passage of the storm Kyrill. In mid-January 2007 the storm affected large part of Europe and caused significant damage in the area of study. The data were available in form of polygons containing most significant forest damage.

The wind speed layer for comparison was calculated using the same procedure as in the proposed method, except that the annual maxima generated from Gumbel distribution were replaced with the real wind speed observed during the storm at the reference station. Figure 10 shows the overlay in the most damaged part of the National Park. Histograms of the wind field in corresponding part of the domain are displayed in Figure 11. The proportion of area with forest damage increases towards higher wind speed and reaches more than 60% for wind speed between 29 and 30 m/s. The top category does not follow this trend, but it only represents small isolated patches, where many other factors of windthrow (soil moisture, forest health, etc.) might have had increased effect.

6 Conclusions and discussion

The main goal of the presented work was to propose a method to generate annual maxima of wind speed over the area of the Bohemian Forest. The generator was planned to simulate extreme wind events in a forest landscape model. The suggested method combined spatial calculations of wind fields using linear model of the WAsP Engineering system and reference wind observations fitted with extremal statistical distribution. Wind speed fields were computed for each sector at generalised wind speed 20 m/s at 30 m above ground as well as at the height of reference anemometer.

The synoptic meteorological station Churáňov was chosen as reference measurement. 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 convection categories were fitted in each direction sector with the Gumbel distribution, which is considered to follow best the block maxima of random variables with Weibull distribution.

In the proposed generator, the fitted Gumbel distributions were evaluated and the resulting annual maxima were used to scale corresponding wind fields. The results of all wind direction sectors were overlaid to generate the final layer of annual wind speed maxima. The method could be also used to generate the extreme wind speed for a single event replacing generated annual maxima with the real wind speed observed at the reference station. The result for the storm Kyrill was compared to the reported forest damage and showed that probability of windthrow depended on the simulated wind speed.

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 with 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.

Acknowledgements

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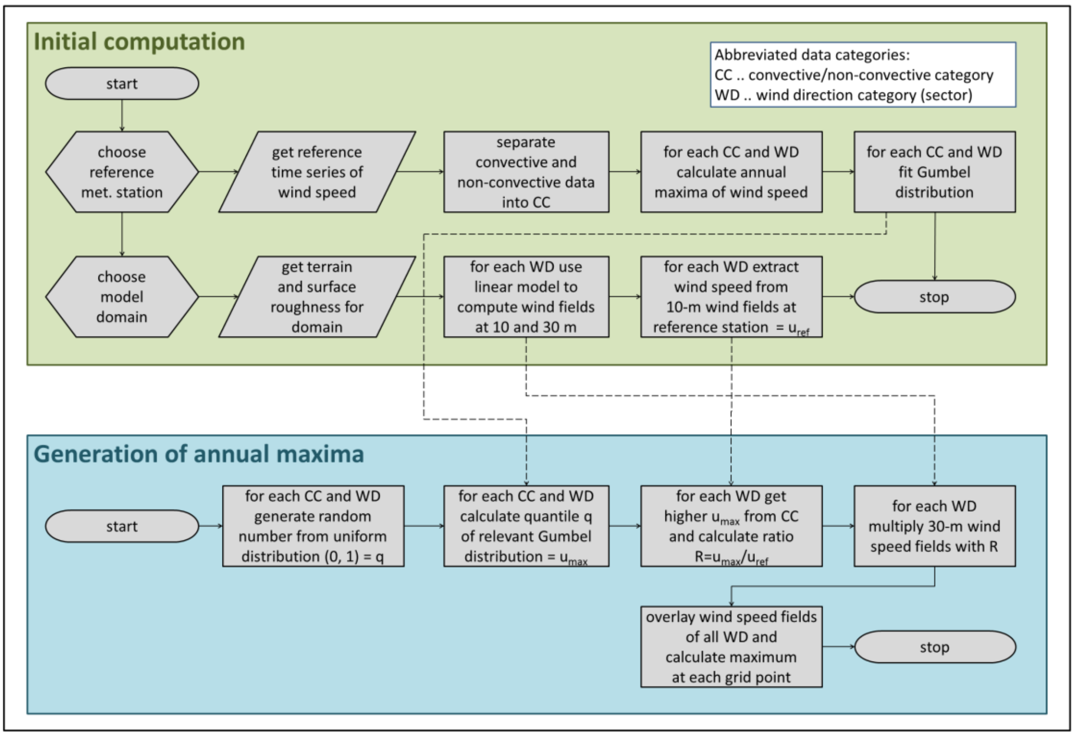

Figure 1. Flowchart of the proposed method.

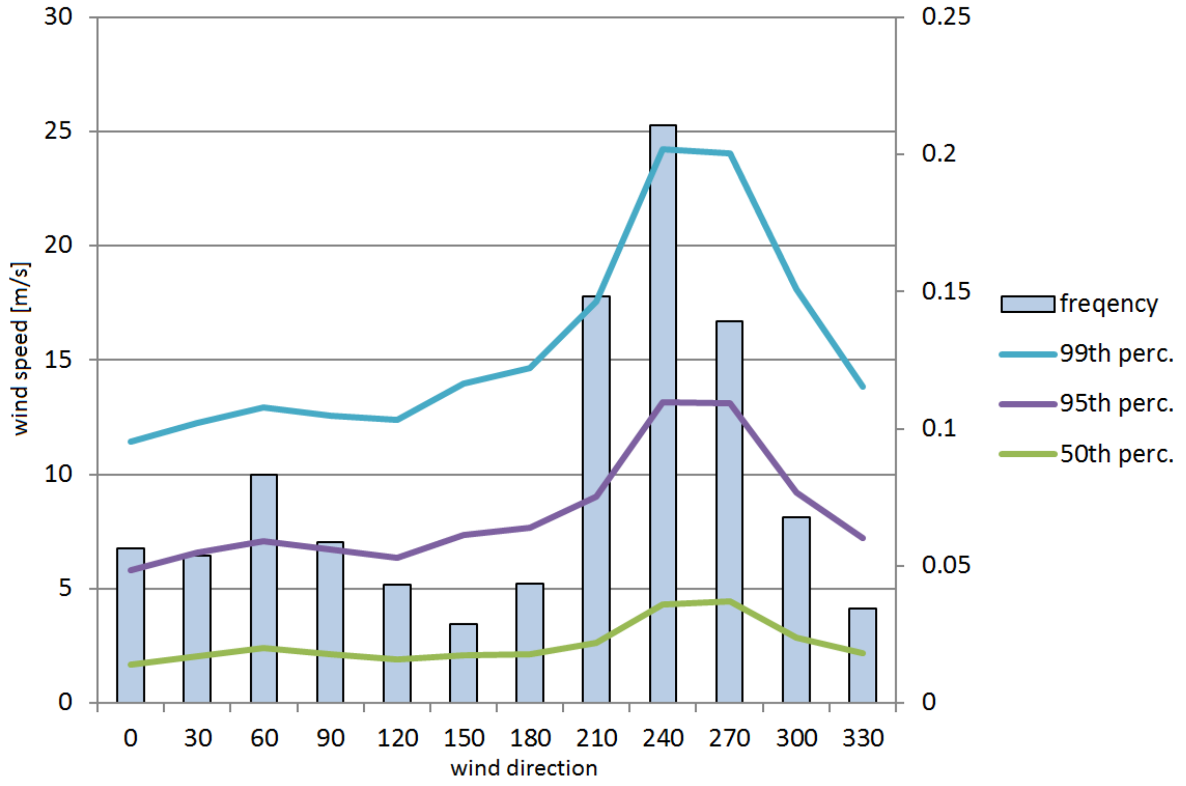

Figure 2. Frequency and the values of 50th, 95th and 99th percentile of wind direction sectors.

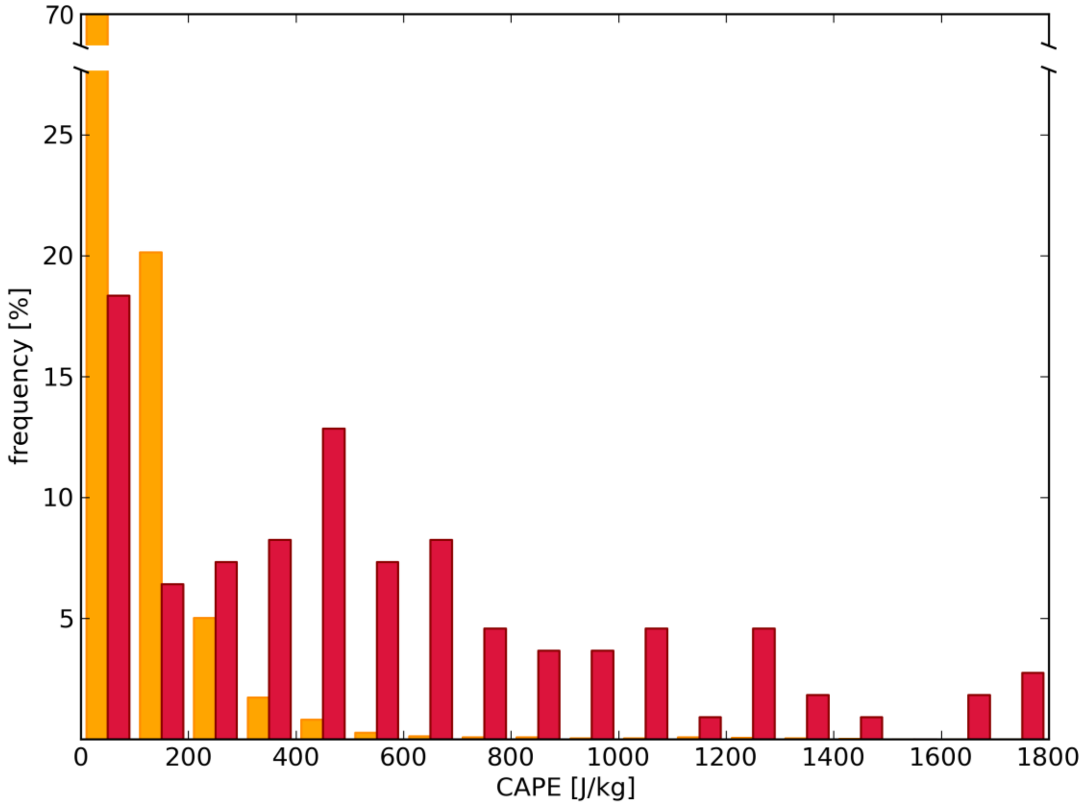

Figure 3. Histogram of index CAPE for thunderstorm (red) and non-thunderstorm (orange) cases at the meteorological station Churáňov in the period 1994-2010. The values of CAPE are extracted from ERA Interim reanalysis archive at the nearest grid point.

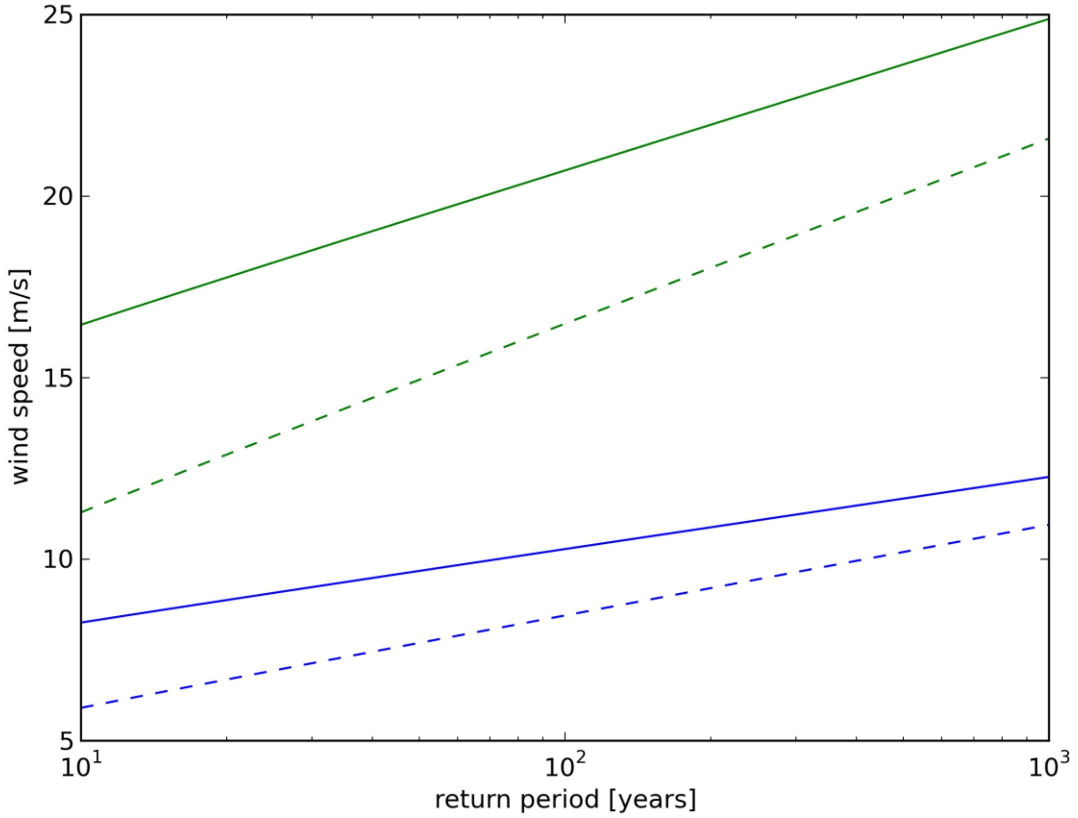

Figure 4. Gumbel distribution fitted to the annual extremes of wind speed at the meteorological station Churáňov in 1979-2010. The green lines show the wind direction sector of 270° with the highest mean wind speed, while blue lines show the sector with lowest mean wind speed centred at 60°. Full lines represent the distributions of non-convective extremes; dashed lines the distributions connected with convective events.

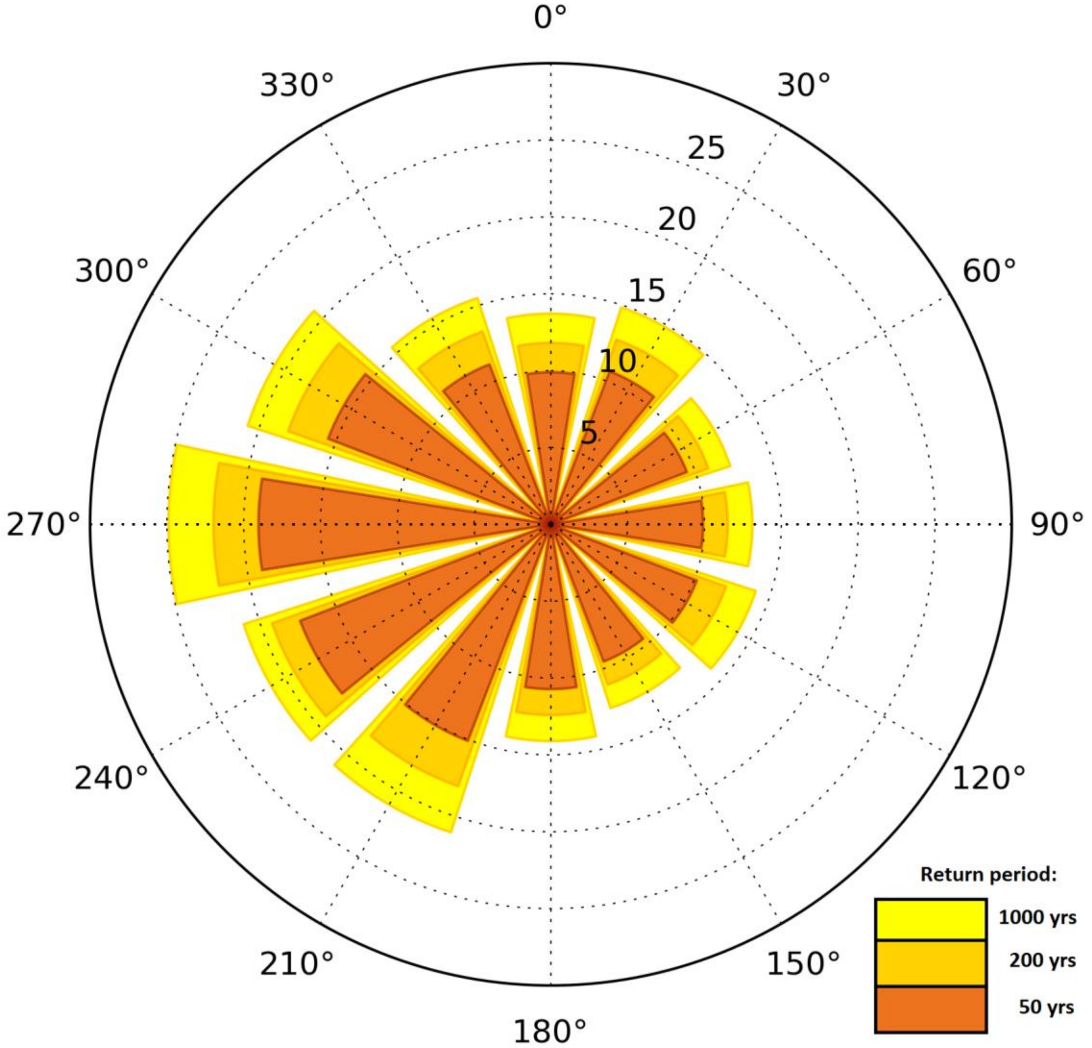

Figure 5. Annual non-convective extreme of mean wind speed (in m/s) with 50-, 200- and 1000-year return period in 12 wind direction sectors.

Figure 6. Position of the model domain within the area of Central Europe.

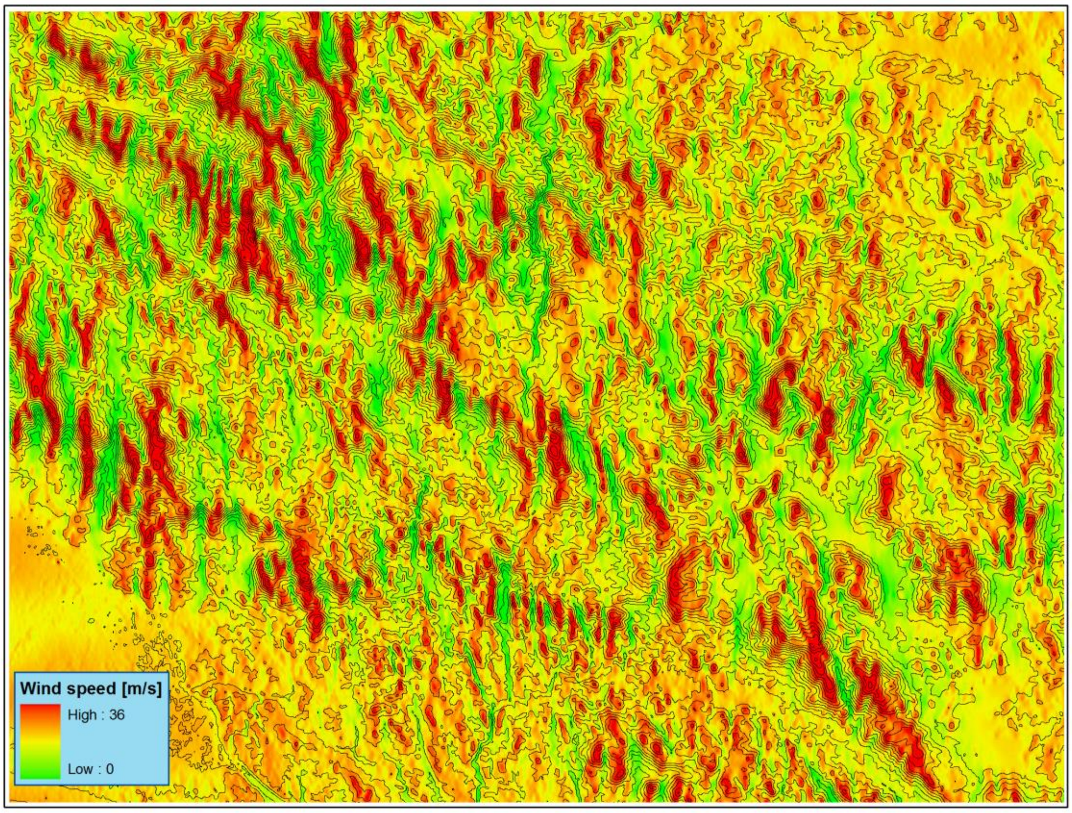

Figure 7. Wind field calculated for the most frequent 270° wind direction at generalised wind speed of 20 m/s. The calculation is done by linear model of WAsP Engineering 3. The terrain is shown as contour lines.

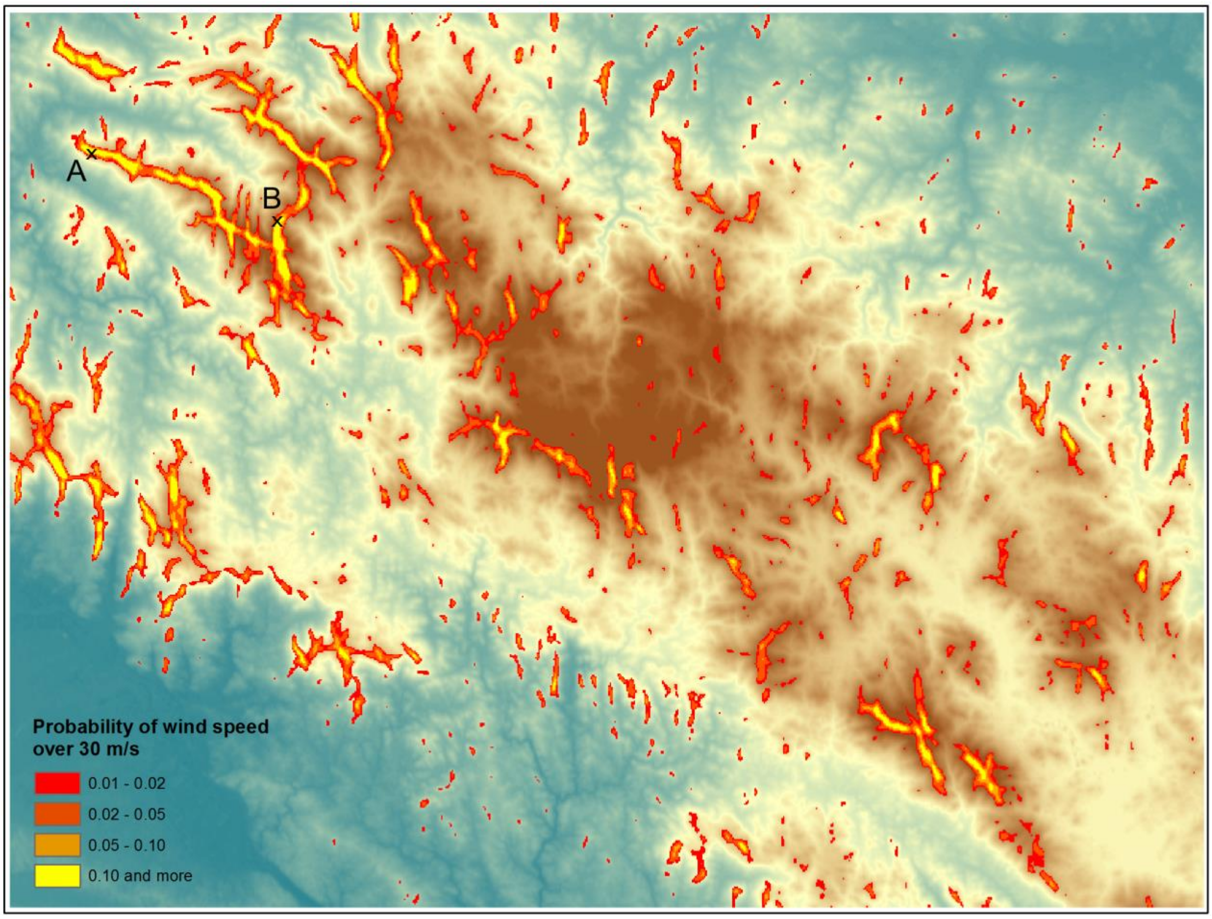

Figure 8. The probability of occurrence of annual wind speed maxima exceeding 30 m/s at 30 m a.g.l. in the results of suggested method. Letters A and B denote the locations discussed in the text. The terrain is shown on the background.

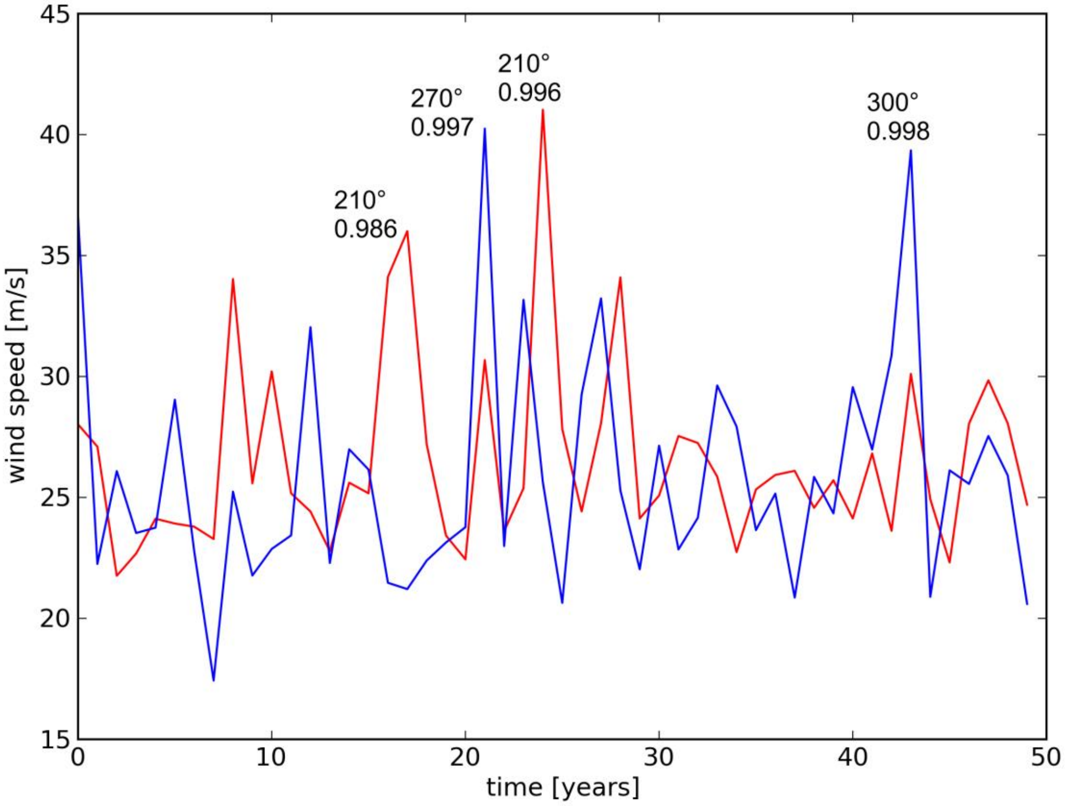

Figure 9. 50-year time series of annual maxima of wind speed at 30 m a.g.l. generated for locations A (red) and B (blue). The highest peaks are annotated with the sector and corresponding quantile value responsible for the simulated event.

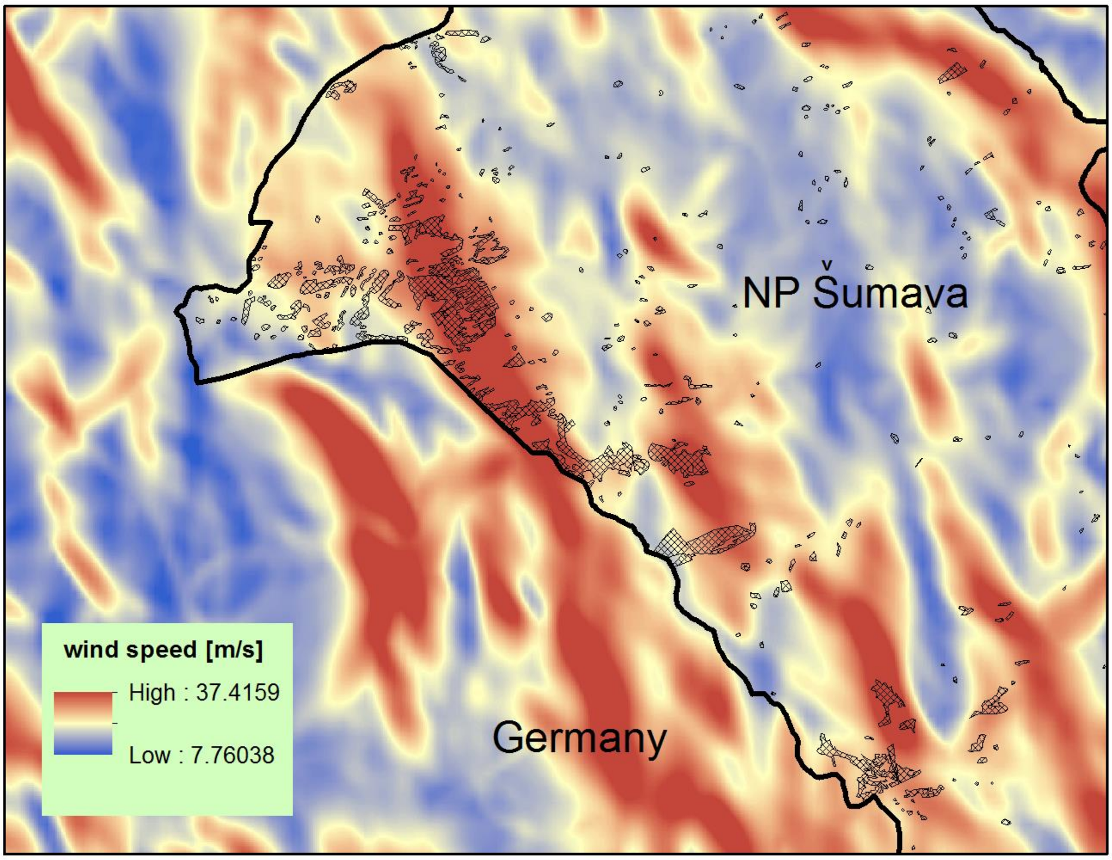

Figure 10. Overlay of the wind speed generated for the storm Kyrill and polygons with reported forest damage. The map shows the most affected area of the National Park Šumava.

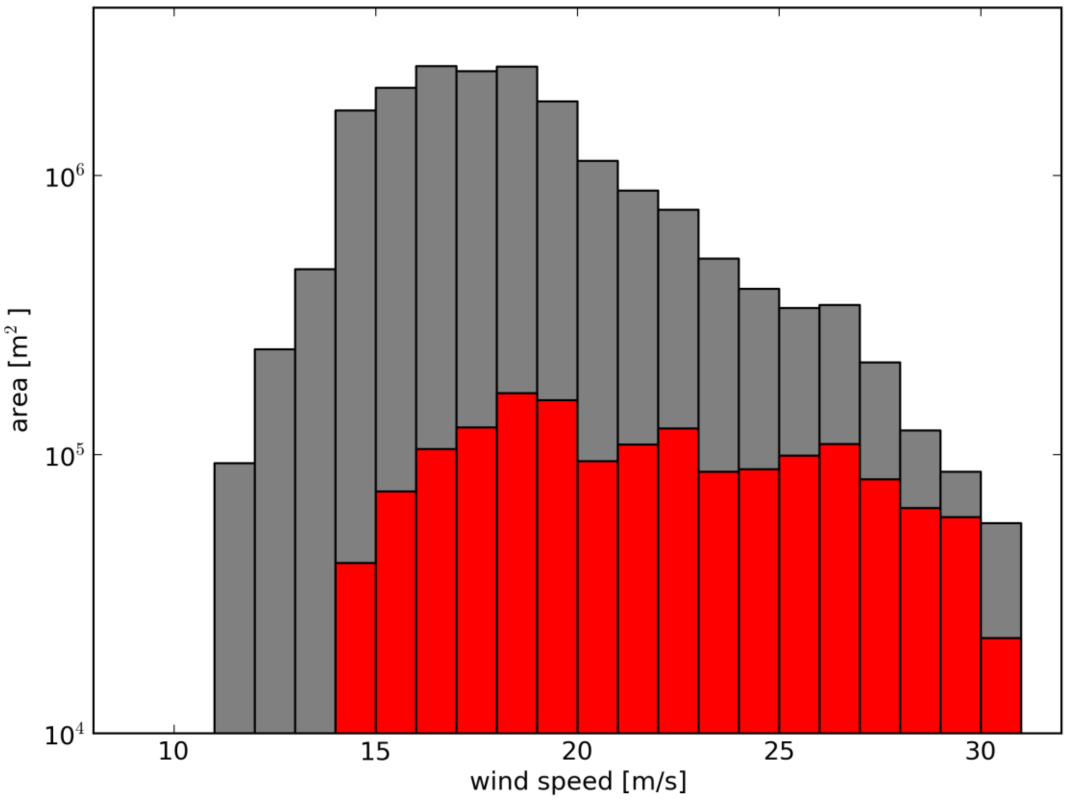

Figure 11. Histogram of the wind speed generated for the storm Kyrill in the most affected area of the National Park Šumava. The grey colour shows the total statistics, while the histogram of values in the polygons with reported forest damage is in red colour. The scale on the vertical axis is logarithmic.