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Summary (max 2000 characters):

This report presents a test and validation of extreme wind calculation applying the Spectral Correction method as implemented in the WAsP Engineering 4 software package.

The test and validation is based on four sites located in Denmark, one site located in the Netherlands and one site located in the USA. Calculations have been carried out using wind data from on-site meteorological masts as well as long-term reference wind data.

Content

Summary

This report presents a test and validation of extreme wind calculation applying the Spectral Correction (SC) method as implemented in the WAsP Engineering 4 software package.

The test and validation is based on four sites located in Denmark, one site located in the Netherlands and one site located in the USA. Extreme wind calculations have been carried out using measured wind data from on-site meteorological (Met) masts as well as long-term reference wind data provided by DTU Wind Energy.

For each of the six sites:

- Two *observed* extreme wind speeds are calculated applying 1) the Annual Maxima (AM) method and 2) the Peak Over Threshold (POT) method to the entire wind data period from the on-site Met mast
- A number of *predicted* extreme wind speeds are calculated applying the SC method to a number of one-year periods from the on-site Met mast
- The *accuracy* of the SC method is validated by comparing the average of the predicted extreme wind speeds (SC method) to the two observed extreme wind speeds (AM method and POT method)
- The *consistency* of the SC method is validated by checking the standard deviation of the predicted extreme wind speeds (SC method only)

Based on the available information, the following main results have been calculated:

Site	On-site Met mast measurement height [m AGL]	Annual Maxima method Observed extreme wind speed, $U_{50max,obs}$ [m/s]	Peak Over Threshold method Observed extreme wind speed, $U_{50max,obs}$ [m/s]	Spectral Correction method		
				Number of one-year periods	Average of predicted extreme wind speeds, $U_{50max,pred}$ [m/s]	Standard deviation of predicted extreme wind speeds, $U_{50max,pred}$ [m/s]
Horns Rev 1	45	N/A	41.4	8	37.5	0.27
Høvsøre	100	42.8	N/A	10	40.3	0.26
Sprogø	70	33.3	34.0	22	35.2	0.22
Tystofte	39	32.1	31.4	32	32.1	0.14
Cabauw	200	39.1	40.1	13	38.4	0.30
Champaign	10	22.5	N/A	18	21.5	0.80

For each of the six sites, it is seen that when applying the SC method:

a) The average of the predicted extreme wind speeds is within 3.9 m/s lower (Horns Rev 1) and 1.9 m/s higher (Sprogø) than the observed extreme wind speeds
b) The standard deviation of the predicted extreme wind speeds is within 0.80 m/s (Champaign)

1 Methodology

This section outlines the applied methodology for test and validation of extreme wind calculation applying the Spectral Correction (SC) method.

In this context, the extreme wind speed, U_{50max}, is defined as the *extreme 10-min average wind speed with a recurrence period of 50 years* (corresponding to the reference wind speed, V_{ref}, as defined in the IEC international standards).

For each of six sites, two *observed* extreme wind speeds, $U_{50max,obs}$, have been calculated applying 1) the Annual Maxima method and 2) the Peak Over Threshold method (see sections 2.1 and 2.2) to the entire period of measured wind data from the on-site Met mast, i.e. as two *observed extreme wind climates* following the methodology of WAsP Engineering (see section 3). This part has been done using the WAsP Climate Analyst 3 freeware tool[1].

Subsequently, and also for each of six sites, a number of *predicted* extreme wind speeds, $U_{50max,pred}$, have been calculated applying the SC method (see section 2.3) to a number of one-year periods from the on-site Met mast, i.e. as a number of *predicted extreme wind climates* following the methodology of WAsP Engineering (see section 3). This part has been done using the WAsP Engineering 4 software package[2].

Finally, and also for each of six sites, the accuracy and consistency of the SC method are validated by a) comparing the average of the predicted extreme wind speeds to the two observed extreme wind speeds and b) checking the standard deviation of the predicted extreme wind speeds.

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[1] Observed extreme wind speeds, $U_{50max,obs}$, are not actually observed as this would require infinitely long periods of measured wind data from the on-site Met masts. However, the observed extreme wind speeds are most likely quite accurate estimates of the extreme wind speeds because they are based on several years of measured wind data from the on-site Met masts.

[2] Predicted extreme wind speeds, $U_{50max,pred}$, have been calculated applying the SC method only. This is because we are testing and validating the SC method only. However, WAsP Engineering 4 also offers the possibility to calculate $U_{50max,pred}$, applying the AM method and/or the POT method.

2 Theory

2.1 Annual Maxima method

Application of the Annual Maxima (AM) method uses the *generalized extreme value cumulative distribution* (GEVD) for fitting the extreme wind values in the form of wind maxima from a basis period of 1 year:

$$F(U) = \exp\left(-(1-k\frac{U-\beta}{\alpha})^{1/k}\right) \qquad \text{(Eq. 1)}$$

, where *F(U)* is the probability that wind speed *U* is not exceeded during one year, *k* is a shape factor, *α* and *β* are distribution parameters. Equation 1 is the integration of the corresponding probability density functions for the extreme wind samples, *U*, given that these samples are independent and identically distributed. The determination of *k* from a short time series was shown to be related to considerable uncertainty and it was shown that *k*=0 is a good approximation for data from a number of Danish sites (Larsén et al. 2015). With *k*=0 we get:

$$F(U) = \exp\left(-\exp(-\frac{U-\beta}{\alpha})\right)$$

The *T*-year return wind U_T for the Gumbel distribution (*k*=0) can be obtained by equating *1/T* with 1-*F(U)*, and for *T*>>1 year, this gives

$$U_T = \alpha \ln T + \beta$$

, where the coefficients *α* and *β* can be obtained in various ways. Here we use the probability weighted moment procedure (Abild 1994; Hosking 1985):

$$\alpha = \frac{2b_1 - \overline{U^{\max}}}{\ln 2}, \quad \beta = \overline{U^{\max}} - \alpha\gamma_E$$

Where $\gamma_E \approx 0.577215665$ is the Euler's constant, and $\overline{U^{\max}}$ is the mean of $U_i^{\max}$. b_1 is calculated from

$$b_1 = \frac{1}{n}\sum_{i=1}^{n}\frac{i-1}{n-1}U_i^{\max}$$

The standard error of the Gumbel fitting was obtained by Ott (2011) via Monte-Carlo simulations to be

$$\sigma_{U_T} = \frac{\alpha\pi}{\sqrt{6N}}\left(1+0.584q_T+\frac{0.234q_T^2}{1-0.823/N}\right)^{1/2}$$

, where

$$k_T = -\frac{\sqrt{6}}{\pi}\left(\ln\ln\left(\frac{T}{T-1}\right)+\gamma_E\right).$$

Kite (1975) showed that the *T*-year estimate can be considered as normally distributed, and accordingly, the 95 % confidence interval can be estimated by $\pm 1.96 \cdot \sigma(U_T)$ (Ott 2011).

2.2   Peak Over Threshold method

The Peak Over Threshold (POT) method is based on the observed wind speed peaks of individual storms.

The method consists in extracting wind speed peaks from a time series of measured wind speed (and direction) of time-wise length T_{obs}, applying a lower wind speed threshold U_0 and a storm separation filter. Thus, the recorded storms have peaks at or above U_0 and are time-wise separated at least by a storm separation time. Also, the storm filter implies a maximum storm duration. A suitable lower wind speed threshold is a value a little lower than the smallest of the annual maxima of the time series (see section 2.1).

The distribution of the extracted wind speed peaks V_i may be represented by an exponential cumulative distribution for a particular wind speed threshold, U_{thresh} (Abild 1994):

$$F(u; U_{thresh}) = 1 - \exp(-\frac{u - U_{thresh}}{A})$$

, and associated with the so-called exceedance rate, $\lambda(u)$, i.e. the number of observed wind speed peaks exceeding U_{thresh} per unit time:

$$\lambda(u) = \lambda_0 \exp(-\frac{u - U_{thresh}}{A})$$

The parameters λ_0 and A may be found from the ranked list of extracted wind speed peaks:

- λ_0 is found as the observed exeedance rate at the selected wind speed threshold, U_{thresh}.
- A is found as the mean exceedance over U_{thresh}: $A = <V_i - U_{thresh}>$, where < > denotes average over the collection of storm peaks

Please notice that U_{thresh} may be different from U_0 when the observed extreme wind climate has been transformed to a target site, e.g. using WAsP Engineering.

The extreme wind for a particular return time, T_{ret} (the wind speed exceeded on the average once per T_{ret} years, normally 50 yers), is then found as (Abild 1994)

$$u_{extr}(T_{ret}) = U_{thresh} + A \ln(\lambda_0 T_{ret})$$

Based on the assumption of the wind speed exceedances to be a Poisson-process the associated uncertainty may be estimated as (e.g. Mann et al. 1998)

$$\sigma(u_{extr}) = \frac{A}{\sqrt{\lambda_0 T_{sampling}}} \sqrt{1 + [\ln(\lambda_0 T_{ret})]^2}$$

2.3   Spectral Correction method

The Spectral Correction (SC) method was developed by Larsén et al. (2012) to correct the smoothing effect arising from the limited resolution and associated artefacts inherent in the mesoscale modelling, to facilitate extreme wind estimation using modelled data. In Larsén et al. (2012), this smoothing effect was shown as the tapered power spectrum in the mesoscale range, reflecting the missing wind variability for the scales connected with (temporal) frequencies of about half a day and higher (Figure 2.1).
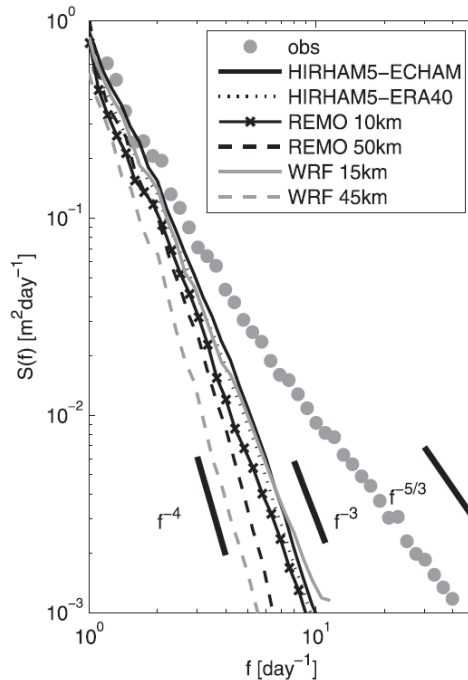

Figure 2.1: The smoothing effect shown in the power spectrum of the modeled wind speed, in comparison with measurements (gray dots) – case study from the offshore Horns Rev site, From Larsén et al. (2012)

The core of this method is to add in the missing variability by replacing the power spectrum calculated from the modelled wind time series in the mesoscale range with the corresponding spectrum from measurements, starting at cross-over frequency, f_c, and ending at high frequency, f_h (Figure 2.2).

Figure 2.2 illustrates the following spectral characteristics that are relevant for the application of the SC method:

1. The spectrum from a 7-year wind measurement extrapolated to 10 m (gray dots)

    a. The fluctuation of the power spectrum $S(f)$ is considerable in the low frequencies up to about 0.04 day^{-1} (note the rule of thumb of the length of the time series 100*(1/(365*7)) day^{-1})
    b. The spectrum has a slope of -5/3 in the range of about 2 day^{-1} to 72 day^{-1}
    c. The spectrum of the low frequency part satisfies $dS(f)/df \to 0$ as $f \to 0$ (thick blue line), a sign of (semi-) stationarity of the time series

2. The spectrum from an overlapping 7-year WRF simulation of wind speed at 10 m (dashed black curve)

    a. The fluctuation is considerable for $f < 0.04$ day^{-1}
    b. The energy level is comparable to the measured one up to $f \sim 2$ day^{-1} – the good agreement for the low frequency part is due mostly to the similar homogeneous water surface condition in the measurements and modeling
    c. The spectrum of the low frequency part satisfies $dS(f)/df \to 0$ as $f \to 0$ (thick blue line), a sign of (semi-) stationarity of the time series

d. The slope of -3 in the range about 2 day^{-1} to 72 day^{-1} – this is the smoothing effect

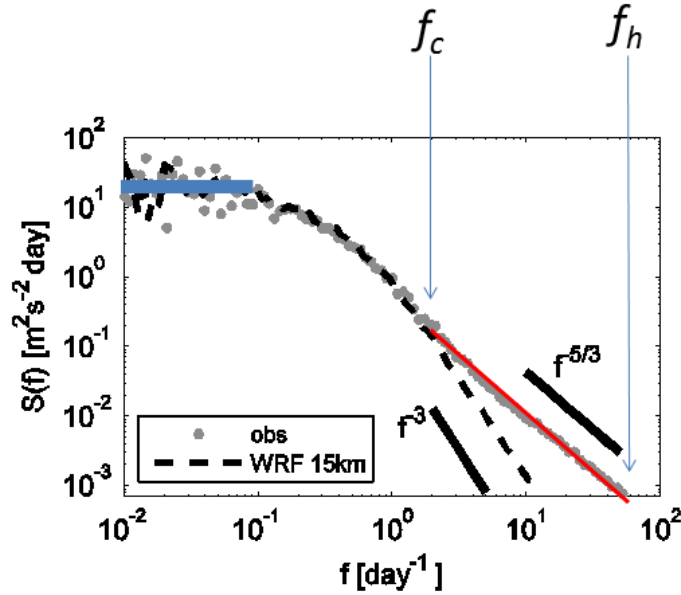3. The red line shows the spectrum model $S(f) = a\,f^{5/3}$ for the range f_c to f_h

Figure 2.2: Characterizing the power spectrum of wind speed – case study for the offshore Horns Rev site

This method can be applicable where measurements as short as a few months are available. In the absence of measurements, the spectral model $S(f) = a\,f^{-5/3}$ can be considered to replace the spectrum from the modelled time series in the range [f_c, f_h]; here a is a coefficient.

The details of the derivation of the algorithms related to this method can be found in Larsén et al. (2012). Briefly, Larsén et al. (2012) assumes that the once-per-year exceedance follows a Poisson process and, with a large threshold, such a distribution of the exceedance can be simplified as a Gaussian process. The maximum wind that occurs once a year, $\overline{U}_{\max}$, was derived as a function of the zero- and second-order spectral moments, m_0 and m_2, through

$$\frac{\overline{U}_{\max} - \overline{U}}{\sigma} = \sqrt{2\ln\left(\frac{1}{2\pi}\sqrt{\frac{m_2}{m_0}}T_0\right)}$$

, where $\overline{U}$ is the mean wind speed, T_0 is the basis period of 1 year, σ is the standard deviation of the time series ($=\sqrt{m_0}$), the zero- and second-order spectral moments, m_0 and m_2 are defined through

$$m_j = 2\int_0^\infty \omega^j S(\omega)d\omega$$

, where $S(\omega)$ is the power spectrum of the wind speed, $\omega = 2\pi f$.

We need to calculate m_0 and m_2 from the spectrum of the original modeled time series (dashed black curve as in Figure 2.2) as well as from the corrected spectrum (dashed black curve up to $f = f_c$ plus the gray dots up to $f = f_h$

when there is measurement; Or the dashed black curve up to $f = f_c$ plus the red line up to $f = f_h$ when there is no measurement).

With a targeted high frequency, f_h, the integration for m_0 and m_2 is done in the discrete manner from $f = 1$ year^{-1} to f_h. In doing so, we do not have the issue of divergence at $f \to \infty$. To repeat, the discrete integration requires the spectrum of as small scatter as possible, which can sometimes be a problem in the low frequencies when the time series is short. In that case, it is recommended to replace the fluctuated values with one constant as suggested by the thick blue line shown in Figure 2.2. When using CFDDA or CFSR data, the data length is 21 years or 32 years, respectively, which usually provides a reliable estimate of $S(f)$ at a frequency of 1/year.

For obtaining the mesoscale spectrum in connection with the use of the SC method, a perfect time series would be: at least one year long with 100 % data coverage.

This is however a condition difficult to meet in practice. In order to limit the uncertainty to a relatively low level by dealing with the various issues in a time series of wind speed, we made some preliminary tests[3]. Based on the results so far from these tests, we recommend preliminarily two simple approaches in preparing the data:

1. The time series should be at least several months long. If there are major gaps in your time series, e.g. with lengths of days or months, then break the time series down and use the portion with best data coverage (this one should at least be a couple of months long, with a data coverage better than 95 %).
2. If your time series has small, randomly distributed gaps (< 5 % of the time series), and if the time series has a data coverage of 90 % or more, then apply linear interpolation to fill in the gaps.

There are other more advanced approaches to deal with missing data, which will be investigated later; these include re-sampling methods, Fourier-based techniques, and statistical synthesis.

2.3.1 Calculating Spectral Correction extreme wind climate

From the long-term (mesoscale) spectrum and the hybrid spectrum, a spectral correction factor is calculated:

$$F_{SC} = \frac{U_{\max}^{Hybrid}}{U_{\max}^{L-T}} \ ,$$

where $U_{\max}^{L-T}$ and $U_{\max}^{Hybrid}$ are the 1-year maximum winds calculated from the long-term (meso-scale) spectrum and the hybrid spectrum, respectively.

The spectral-corrected annual maximum winds, forming the SC method extreme wind climate, are then found as

$$U_{1y-\max;i}^{SC} = F_{SC} U_{1y-\max;i}^{L-T}$$

where i is the index of the years of the long-term time series.

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[3] In the tests, we used one year measurements of 10-min wind from the Tystofte site, where the data coverage is 100 %. We first examined the impact of long periods of missing data (gaps with length varying from one day to months), with its position at the end or in the middle of the time series. Then we examined the impact of a number (from 1 to 10) of randomly distributed gaps, with the gap-length 1-5 % of the data, accumulating the missing data 1 % to 50 % of the entire time series. We tried two simple ways to treat the gaps: (a) leaving them out; (b) filled in the gaps with linear interpolation using the two values before and after the gap.

3 WAsP Engineering

The *WAsP Engineering* software package calculates wind conditions, which are relevant for fatigue loads, extreme loads and siting of wind turbines and wind farms, including extreme winds at individual wind turbine positions on any particular site. The typical application is calculation of wind conditions for IEC site assessment, e.g. wind shear, ambient turbulence, extreme wind and wind flow inclination for individual wind turbines in a wind farm (complete assessment also requires WAsP). This information helps to select wind turbines, which are suitable for the local wind conditions on the site.

The flow model in WAsP Engineering, LINCOM (Astrup et al. 1997), is a linear flow model based on principles similar to those of the IBZ flow model in the WAsP software package, based on Jackson&Hunt theory (Jackson & Hunt 1975). In combination with the so-called geostrophic drag-law, LINCOM forms a combined flow model, which is used to transform wind data from an observation point to any particular target sites, typically wind turbine positions. One difference from the IBZ flow model is that for the LINCOM flow model the surface roughness over water depends on wind speed and the fetch to the nearest upwind shore. The reason for this refinement is that WAsP Engineering focuses on precise extreme wind estimates, where the dependency of surface roughness on wind speed becomes significant.

The extreme wind model in WAsP Engineering is based on *observed extreme wind climate* statistics with adjustments for terrain-induced speed-up. In order for WAsP Engineering to calculate the effects of the surrounding terrain on the wind at a given place it is necessary to describe systematically the most important features of the surrounding terrain, i.e. orography and roughness.

WAsP Engineering applies the LINCOM flow model, combined with the geostrophic drag-law to transform an observed extreme wind climate to standard conditions defined as flat terrain with uniform surface roughness. The result is a *generalized extreme wind climate*. Subsequently, WAsP Engineering applies the LINCOM flow model, combined with the geostrophic drag-law to transform the generalized extreme wind climate to the *predicted extreme wind climate* at the wind turbine positions. This is how calculating extreme winds (e.g. U_{50max}) – applying the Annual Maxima (AM) and Peak Over Threshold (POT) methods as described in section 2 – are performed in WAsP Engineering 4 and earlier versions.

The Spectral Correction (SC) method for calculating extreme winds (e.g. U_{50max}), as described in section 2, has recently been integrated into the WAsP Engineering software package. Extreme wind calculation applying the SC method was introduced in WAsP Engineering 4 and this is slightly more complicated.

3.1 Generalized extreme wind climate using Spectral Correction method

Generating a generalized extreme wind climate using the SC method involves three steps:

- Generalization of long-term reference wind data (performed by DTU Wind Energy, so that generalized long-term reference wind data are readily available to the WAsP Engineering 4 user in the cloud)
- Generalization of on-site measured wind data
- Calculation of generalized extreme wind climate

3.1.1 Generalization of long-term reference wind data

The generalized long-term reference extreme wind climate is calculated from the long-term reference wind data in generalized form. In this study, two long-term reference wind data sets have been used: the CFDDA reanalysis data set [1] and the CFSR reanalysis data set [2, 3]. The generalization of the long-term reference wind data was performed using the LINCOM flow model, combined with the geostrophic drag-law (the same combined flow model as used in WAsP Engineering). The necessary surface roughness values for the grid points of the reanalysis data sets were obtained in two ways. For the CFDDA data set, the roughness for an on-shore grid point was derived

from the $<U_{max}>$ -values at 10, 50 and 100m, where $<U_{max}>$ is the mean of the annual maxima at the three heights, and for offshore grid points it was derived from Charnock's formulation with a coefficient of 0.05 for a 50-year extreme wind speed. For a grid point representing both offshore and onshore, a smoothing, consisting in taking the larger of the two, was applied. The CFSR data were applied to one offshore site only, and here the roughness was estimated as for the CFDDA data. The terrain data[4] used in the generalization procedure were the ones supplied as part of the reanalysis data sets.

In some introductory studies, using the CFSR as long-term reference wind data, roughness length and orography data, averaged over the entire period, supplied with the CFSR reanalysis data set, were used for the generalization. However, over land, the values of the roughness length as used in the reanalysis appeared in some cases to be very different from usual measurements, due to the underlying models and parameterizations being different from those implied by a simple logarithmic profile. For instance, the roughness length from the CFSR reanalysis could be as high as 1 m over major parts of Denmark. This means that using this value in the generalization would give a severe overestimation of the generalized wind, since a different (smaller) roughness is needed to relate the (effective) reanalysis' geostrophic wind to the surface-layer velocity scales. This issue has been analogously treated in Badger *et al*. (2015, The Global Wind Atlas). In Badger et al. (2015), it is found that the need, and extent to which the roughness length must be adjusted, varies with reanalysis type and geographical location. In general, they found preliminarily that the extent of roughness 'translation' needed was least with the CFDDA data. It is shown here to be the case for Denmark. Consequently, in the present implementation of the SC method, WAsP Engineering applies CFDDA long-term reference data only.

In WAsP Engineering 4, generalized reanalysis data are provided by DTU Wind Energy. At release in June 2016, the data cover Europe (incl. Turkey) and the USA. DTU Wind Energy will gradually expand coverage and expect to include China in 2016. Global coverage is expected in 2017.

3.1.2 Generalization of on-site measured wind data
The combined flow model of WAsP Engineering is used to transform the on-site measured wind data to a generalized short-term wind data set, referring to standard conditions. Here a detailed terrain map, containing elevation and roughness features around the mast location, is used.

3.1.3 Calculation of generalized extreme wind climate
The generalized extreme wind climate is calculated as described in section 2.3 and 2.3.1, using a) the power spectrum for the generalized long-term reference wind data, b) the power spectrum for the generalized on-site measured wind data, and c) the hybrid spectrum.

3.2 Uncertainty of Spectral Correction method
Several sources of uncertainty exist within application of the SC method. As indicated above, a primary source of uncertainty involves the roughness lengths associated with use of reanalysis data, rather than the method itself. Specifically, the roughness length *needed* to properly generalize the reanalysis data might be different than the roughnesses given with the data, and likely differs from the (mean, 'mesoscale') roughnesses derivable from roughness maps used for microscale atmospheric modelling (e.g. in WAsP Engineering or WAsP).

The sensitivity of the generalized wind speed to roughness may be seen by examining the reduced geostrophic drag-law (Jensen *et al*., 1984) employed in the generalization. Looking at this sensitivity allows an approximate gauging of the uncertainty involved, as elucidated in Kelly & Jørgensen (2014 and 2016) and implicit in §6 of Badger *et al*. (2015). The basic sensitivity is expressible via

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[4] For the CFDDA and CFSR data used in the current study, we choose a domain size that does not expand more than 16 degrees in latitude in order to ensure the difference in grid spacing less than 5 km. This is for the convenience of the use of LINCOM.

$$\frac{\partial U_{\text{hub}}}{\partial \ln z_0} \simeq \frac{0.485G}{\kappa} \frac{A + \ln\left(\frac{z_{\text{hub}}}{fG}\right)}{\left[\ln\left(\frac{G}{fz_0}\right) - A\right]^2}$$

, where G is the (effective) geostrophic wind speed, f is the Coriolis parameter, and the drag-law parameter, A, is typically taken to be 1.8. For roughnesses that are too large by an order of magnitude, the above relation suggests that wind speeds are overpredicted by approximately 30 % or more (depending on the actual roughness).

Other uncertainties inherent in the SC method appear to be smaller, in general, than that due to the assignment of geostrophic-scale roughness length for generalization. There is some uncertainty involved with choosing the f_c, but for well-behaved spectra (no severe peaks near $f \sim 1$ day^{-1}), this is a smaller issue than that involving the reanalysis roughness; thus it is suggested to check the spectra, and if they are ill-behaved, to use a different part of the time series.

Without spectral-fitting, the primary source of uncertainty is the Gumbel-fitting of extreme events. This depends basically on the ratio of Gumbel-slope (α) to square-root of years used (as shown in section 2.1), but becomes minor when using the long time series of reanalysis data.

4 Sites and wind data

The test and validation of extreme wind calculation applying the Spectral Correction (SC) method is based on six sites; four sites are located in Denmark, one site is located in the Netherlands, and one site is located in the USA.

The sites have been selected based on the following criteria: 1) On-site measured wind data are available, 2) On-site measured wind data are not confidential and 3) On-site measured wind data cover several years.

It was also intended that the sites should preferably be representative of different regions of the world. However, outside of Denmark it was unfortunately difficult to obtain wind data fulfilling the above criteria. Therefore, the test and validation is mainly based on sites located in Denmark.

4.1 Sites

1. The Horns Rev 1 site is located in the North Sea about 14 km west of the southern part of Jutland, Denmark.

2. The Høvsøre site is located in western Jutland, Denmark, approximately 2 km east of the North Sea coastline. The terrain is quite flat and largest elevation changes (10-15 m) occur at the sand dunes parallel to the coast line. The terrain surface roughness lengths are fairly uniform with a value of 0.02 m. A few patches with roughness length of 0.05 exist to the east and north-east of the Met mast.

3. The Sprogø site is located on the island of Sprogø in the Great Belt between the islands of Zealand and Funen, Denmark. The distances to Zealand and Funen are about 7.5 km and 9.5 km, respectively. At the 70 m AGL measurement height, the roughness variations on Zealand and Funen may have an influence. Thus, in addition to water surfaces (0 m) the roughnesses of farm land (0.05 m); farmland with bushes (0.1 m); towns and villages (0.4 m); and forests/woods (1.0 m) were taken into account.

4. The Tystofte site is located in south-western Zealand, Denmark. The terrain is relatively flat with elevation variations about zero to thirty meters above sea level within the nearest 3 km. The land cover is mainly farmland but there is also the town Skælskør about 2 km to the north-west. The surroundings are dominated by the Great Belt and Smålandsfarvandet waters, which lie approximately 6 km to the west and 5 km to the south, respectively. The terrain surface roughness lengths are estimated at a background roughness length of 0.03 m for the farmland and 0 (zero) m for the Great Belt and Smålandsfarvandet waters.
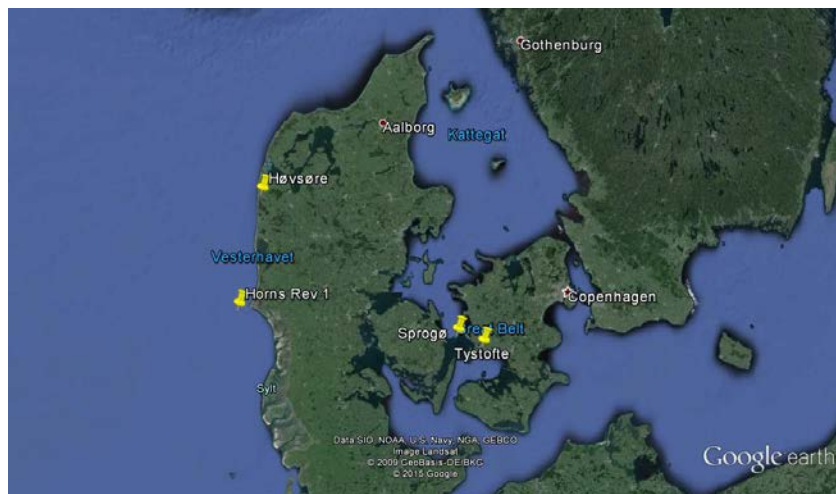

Figure 4.1.1: Google Earth image of locations of four sites in Denmark (yellow pins)

5. The Cabauw site is located in the Netherlands about 50 km east-southeast of the North Sea. The terrain surrounding the Met mast is flat and is mainly covered by farmland, open pastures and low houses. A background terrain roughness length of 0.05 m is used to model the farmland and the open pastures, while roughness lengths of up to 1.75 m is used to model houses and patches of forest.
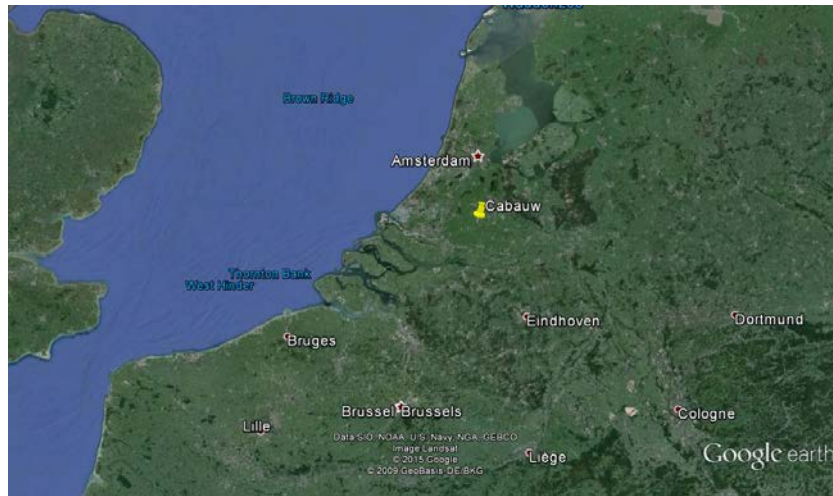

Figure 4.1.2: Google Earth image of location of the Cabauw site in the Netherlands (yellow pin)

6. The Champaign site is located in Illinois, midwestern USA, and is associated with Willard airport, south of the small city of Champaign and the University of Illinois. The site is a METAR (meteorological aviation routine) weather station (name: KCMI) and lies south of the small local airport, which possesses two runways; the station is roughly 500 m southwest and southeast from the closest points of each runway, respectively. The outskirts of Champaign lie approximately 5 km to the NNE, and there is a golf course with some trees located roughly 1-2 km to the NE. The terrain is flat, with elevations varying from 210-220 m above sea level within the nearest 10 km. The background roughness length of the dominant terrain-type, farmland, is set to be 0.014 m. The roughness of the airport runways is set to be 0.01 m. The suburban-type roughness due to Champaign-Urbana does not significantly appear to affect the winds, since this wind direction is uncommon; however, there are extreme wind events which occur from the direction of Urbana. The roughness in this area is set to be 0.6 m.

Figure 4.1.3: Google Earth image of location of the Champaign site in the USA (yellow pin)

4.2 On-site measured wind data

We use cup anemometer and conventional wind vane measurements (mostly 10-minute averages) from all six on-site Met masts.

The entire periods of wind data (wind speed and wind direction) from all Met masts were manually filtered to remove invalid values such as those caused by equipment faults and anomalies, and/or weather conditions such as icing. Subsequently, periods of missing or filtered data (gaps) were identified and data recovery rates for the entire periods as well as for individual years were determined. Note that the data gaps have *not* been filled (by linear interpolation or any other method).

The locations of the on-site Met masts and a summary of the measurements are listed in Tables 4.2.1 and 4.2.2.

Site	UTM WGS 84 zone	Easting [m]	Northing [m]
Horns Rev 1	32	428 949	6 151 899
Høvsøre	32	447 642	6 255 431
Sprogø	32	625 201	6 133 395
Tystofte	32	648 065	6 123 903
Cabauw	31	632 369	5 759 567
Champaign	16	391 530	4 432 308

Table 4.2.1: Locations of on-site Met masts

Site	Measurement height [m AGL]	On-site wind data period	Data recovery rate [%]
Horns Rev 1	45	14 MAY 1999 - 23 JUN 2006	92
Høvsøre	100	01 JAN 2005 - 31 DEC 2014	97
Sprogø	70	13 SEP 1977 - 08 SEP 1999	98
Tystofte	39	01 JAN 1983 - 11 OCT 2014	94
Cabauw	200	01 JAN 2001 - 31 DEC 2013	99
Champaign	10	01 JAN 1997 - 31 DEC 2014	73

Table 4.2.2: Summary of on-site wind measurements after filtering

1. The Horns Rev 1 Met mast was established in connection with the construction of the Horns Rev 1 offshore wind farm. Wind data are recorded as 10-minute averages, and for the present purpose only the wind data measured at 45 m were used and the following results (see section 5.1) are based on the 7-year on-site wind data period. Note that over the 7-year period, about 13 months of data were missing – and not completely at random. However, although this may give some seasonal bias, most individual years have a data recovery rate higher than the 90 per cent minimum rate recommended by DTU Wind Energy for application of the SC method (see section 2.3).

   As it is mostly the case, a Weibull distribution is a good approximation to the wind data. The all-sector wind speed distribution (including Weibull-*A* and *k* parameters) is seen in Figure 4.2.1. This figure also shows the sector-wise wind direction distribution (wind rose) for the Horns Rev 1 Met mast at 45 m ASL, indicating that a broad sector from southwest to northwest is the dominant wind direction.
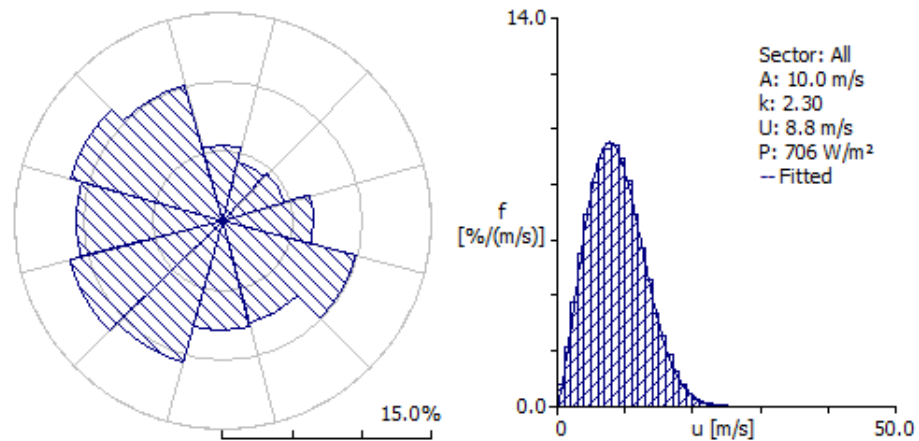
Figure 4.2.1: Observed mean wind climate for the Horns Rev 1 Met mast at 45 m ASL, based on 7-year wind data period

2. We use data from the 116 m tall Høvsøre Met mast located to the south of the DTU Wind Energy Test Site for Large Wind Turbines. Wind data is recorded as 10-minute averages, and for the Høvsøre site the following results (see section 5.2) are based on the 10-year on-site wind data period. For all individual years, the data recovery rate is high and above the 90 per cent minimum rate recommended by DTU Wind Energy for application of the SC method.

    As it is mostly the case, a Weibull distribution is a good approximation to the wind data. The all-sector wind speed distribution is seen in Figure 4.2.2. This figure also shows the sector-wise wind direction distribution for the Høvsøre Met mast at 100 m AGL, indicating that a broad sector from southwest to northwest is the dominant wind direction.
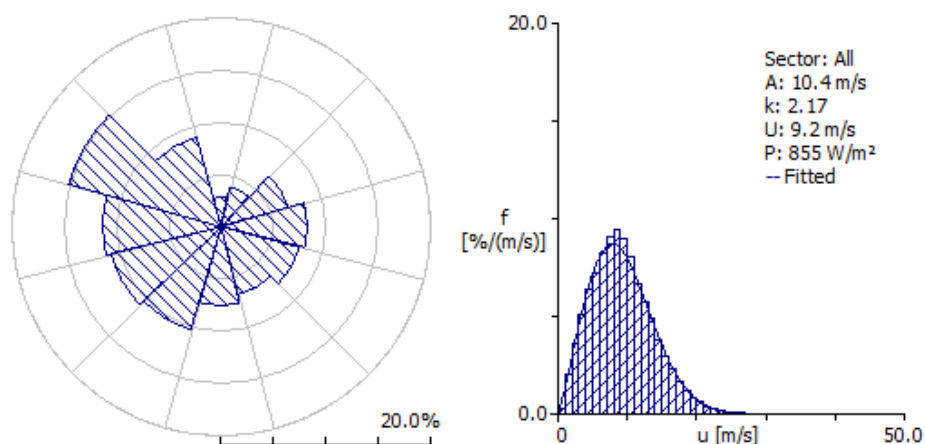

Figure 4.2.2: Observed mean wind climate for the Høvsøre Met mast at 100 m AGL, based on 10-year wind data period

3. The 70 m tall Sprogø Met mast was established in 1977 and taken down in 1999, with wind data recorded as 10-minute averages. For the period from 1977 to 1988, the wind data were processed to extrapolate the measurements at 67.5 m AGL to 70.0 m AGL; this was achieved by a correlation established over a period where wind data from 67.5 m as well as 70.0 m were measured. Also, for 2 periods (covering 1 year in total), the wind direction data associated with the 70 m wind speed data were bad or missing, so the wind direction data at 10 m were substituted.

    For the Sprogø site, the following results (see section 5.3) are based on this 22-year on-site wind data period. Note that during four individual years, about one month of data is missing. However, although this may give

some seasonal bias, all the individual years have a data recovery rate higher than the 90 per cent minimum rate recommended by DTU Wind Energy for application of the SC method.

As is mostly the case, a Weibull distribution is also for the Sprogø Met mast a good approximation to the wind data. The all-sector wind speed distribution is seen in Figure 4.2.3. The figure also shows the sector-wise wind direction distribution for the Sprogø Met mast at 70 m AGL, indicating that a broad sector from southwest to northwest is the dominant wind direction.
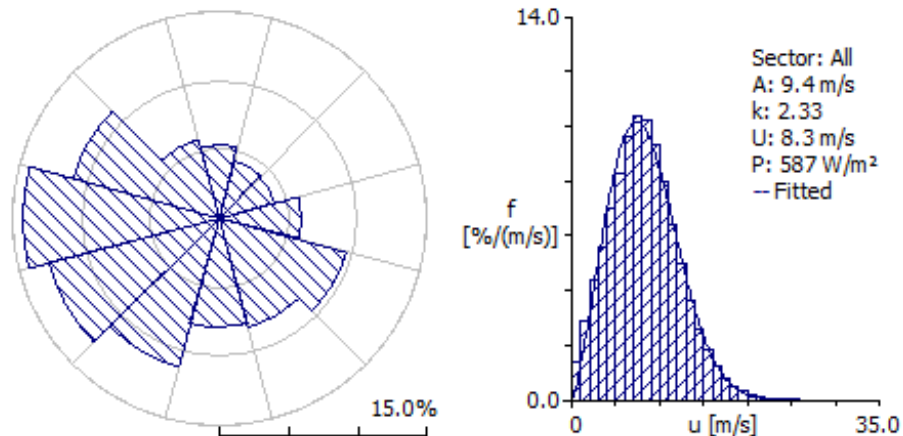

Figure 4.2.3: Observed mean wind climate for the Sprogø Met mast at 70 m AGL, based on a 22-year wind data period

4. The Tystofte site has the Tystofte Met mast installed on-site with wind data measured and recorded as 10-minute averages at measurement height 39 m AGL during the period from 1982 to 2015. For the Tystofte site, the following results (see section 5.4) are based on this 32-year on-site wind data period. Note that for a few individual years, the data recovery rate is below the 90 per cent minimum rate recommended by DTU Wind Energy for application of the SC method.

A Weibull distribution is often a good approximation to wind speed data and this is also the case for the wind data measured at the Tystofte Met mast. The all-sector wind speed distribution is seen in Figure 4.2.4. The figure also shows the sector-wise wind direction distribution for the Tystofte Met mast at 39 m AGL, indicating that a broad sector from southwest to northwest is the dominant wind direction.
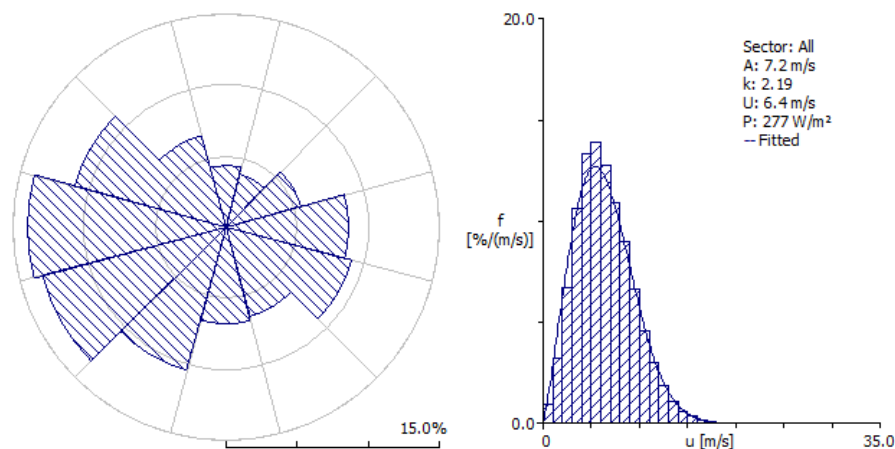

Figure 4.2.4: Observed mean wind climate for the Tystofte Met mast at 39 m AGL, based on 32-year wind data period

5. The 213 m tall Cabauw Met mast is located in the western part of the Netherlands. Wind measurements have been conducted since 1972 but in this exercise we use 13 years of observations measured and recorded as 10-minute averages at 200 m AGL during the period from 2001 to 2013. The following results (see section 5.5) are based on this 13-year on-site wind data period. All the individual years have data recovery rates above the 90 per cent minimum rate recommended by DTU Wind Energy for application of the SC method.

    A Weibull distribution is often a good approximation to wind speed data and this is also the case for the wind data measured at the Cabauw Met mast. The all-sector wind speed distribution is seen in Figure 4.2.5. The figure also shows the sector-wise wind direction distribution at 200 m AGL, indicating that Southwest is the dominant wind direction.
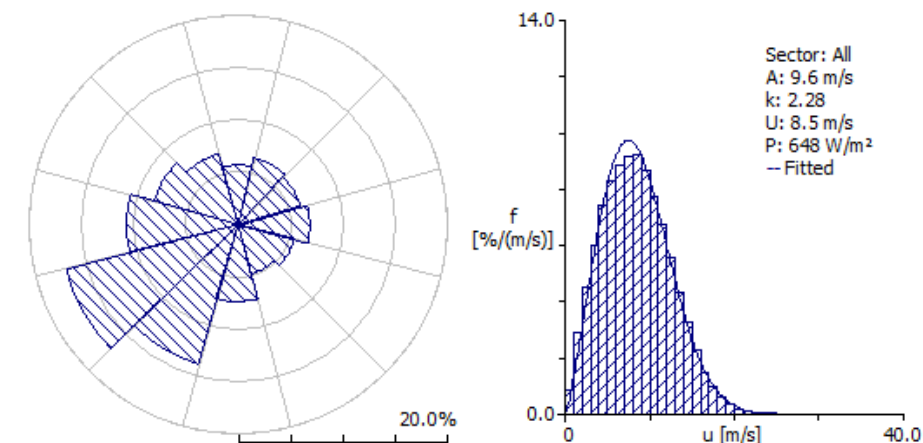

Figure 4.2.5: Observed mean wind climate for the Cabauw Met mast at 200 m AGL, based on a 13-year wind data period

6. The mid-American Champaign/KCMI Met mast provides wind measurements from 10 m AGL. Wind data is recorded as 1-hour averages, and was obtained for the period from 1997 to 2014. Wind speeds are recorded in knots (1 kt = 0.5144 m/s) with a discretization of 1 knot, and wind directions were recorded with a discretization of 10 degrees. The wind speeds were thus converted to m/s. The data recovery rate was relatively low in some years; per year, it varied from 68 % up to 93 %, but fortunately there was no systematic or seasonal pattern to the data gaps. The following results (see section 5.6) are based on this 18-year period of on-site wind data. Note that for most years, the data recovery rate fell below 90 per cent, which is the minimum rate recommended by DTU Wind Energy for application of the SC method.

    A Weibull distribution is typically a good approximation to wind speed data, and this is also the case for the Champaign/KCMI data here. The all-sector wind speed distribution is shown in Figure 4.2.6, along with the corresponding sector-wise wind direction distribution. As seen in the figure, the wind rose implies dominant winds from the south, northwest, and northeast.
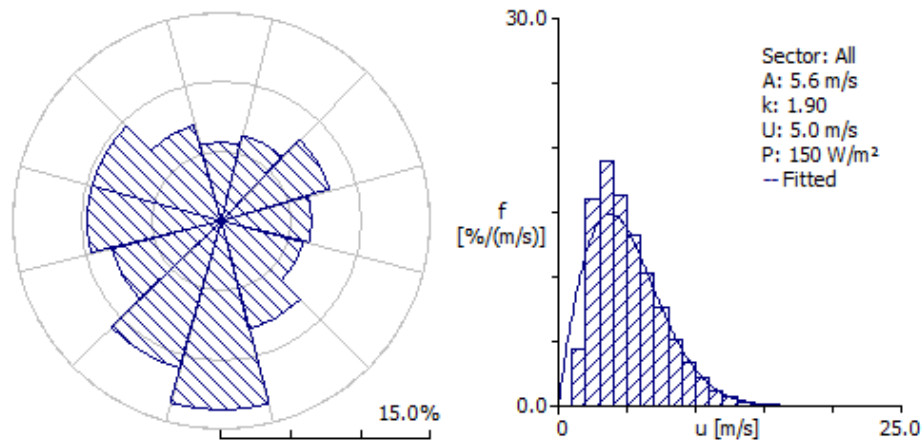
Figure 4.2.6: Observed mean wind climate for the Champaign/KCMI Met mast at 10 m AGL, based on 18-year wind data period

4.3 Long-term reference wind data

For the SC method, there is no need for the WAsP Engineering user to provide any *long-term* wind data in order to generate an observed extreme wind climate (the user does need to have *short-term* wind data, e.g. from an on-site wind measurement). Instead, WAsP Engineering uses CFDDA long-term reference wind data, which is made available by DTU Wind Energy on a computer server in the cloud.

For the present study, two types of reanalysis wind data are used as the long-term reference (other types of modelled data could also be used for this purpose, e.g. long term weather forecasting modelled data), i.e. the 10 m wind data from the following two products:

- The Climate Four-Dimensional Data Assimilation (CFDDA) data (http://rda.ucar.edu/)
- The Climate Forecast System Forecast (CFSR-I) data (Saha et al. 2010a, 2010b)

The CFDDA 10 m winds cover 1985-2005, i.e. 21 years. They are hourly with a spatial resolution of 40 km and were obtained for the CFDDA grid-points nearest to the Horns Rev 1, Høvsøre, Sprogø, Tystofte, Cabauw, and Champaign sites (all six sites).

The CFSR-I 10 m winds are available from 1979 to 2010, i.e. 32 years. They are hourly with a spatial resolution of about 38 km and were obtained for the CFSR grid-point nearest to the Horns Rev 1 site.

Site	Source	Period	Temporal resolution	Spatial resolution
Horns Rev 1	CFDDA	1985 - 2005	1 hour	40 km
	CFSR	1979 - 2010	1 hour	38 km
Høvsøre	CFDDA	1985 - 2005	1 hour	40 km
Sprogø	CFDDA	1985 - 2005	1 hour	40 km
Tystofte	CFDDA	1985 - 2005	1 hour	40 km
Cabauw	CFDDA	1985 - 2005	1 hour	40 km
Champaign	CFDDA	1985 - 2005	1 hour	40 km

Table 4.3.1: Summary of long-term reference wind data

Together with the reanalysis wind data, we also used the terrain data from the two products in relation to the generalization procedure as described in paragraph 3.1.1.

5 Results

This section presents the results of extreme wind calculations applying the Annual Maxima (AM) method, the Peak Over Threshold (POT) method and the Spectral Correction (SC) method, respectively.

For each of six sites, two *observed* extreme wind speeds, $U_{50max,obs}$, have been calculated applying 1) the AM method and 2) the POT method directly to the entire period of measured wind data from the on-site Met mast, i.e. as two observed extreme wind climates following the methodology of WAsP Engineering (see section 3). This part has been done using the WAsP Climate Analyst 3 freeware tool.

Subsequently, and also for each of six sites, a number of *predicted* extreme wind speeds, $U_{50max,pred}$, have been calculated applying the SC method to a number of one-year periods from the on-site Met mast, i.e. as a number of predicted extreme wind climates following the methodology of WAsP Engineering (see section 3). This part has been done using the WAsP Engineering 4 software package.

5.1 Horns Rev 1 (North Sea, Denmark)

5.1.1 Observed extreme wind speeds

For the Horns Rev 1 Met mast at 45 m ASL, $U_{50max,obs}$ is 45.5 ±7.04 m/s applying the AM method and 41.4 ±4.62 m/s applying the POT method to the entire 7-year on-site wind data period.

The all-sector extreme wind distributions applying the AM and POT methods are seen in Figures 5.1.1 and 5.1.2 respectively. These two figures also show the extreme wind direction distribution for the Horns Rev 1 Met mast at 45 m ASL, indicating that a broad sector from southwest to northwest is the dominant extreme wind direction.
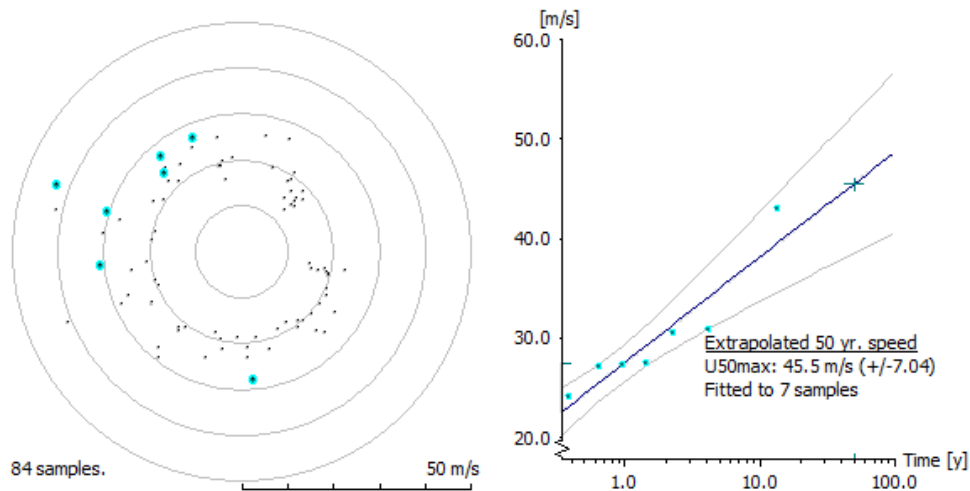

Figure 5.1.1: Observed extreme wind climate applying AM method for the Horns Rev 1 Met mast at 45 m ASL, based on 7-year wind data period
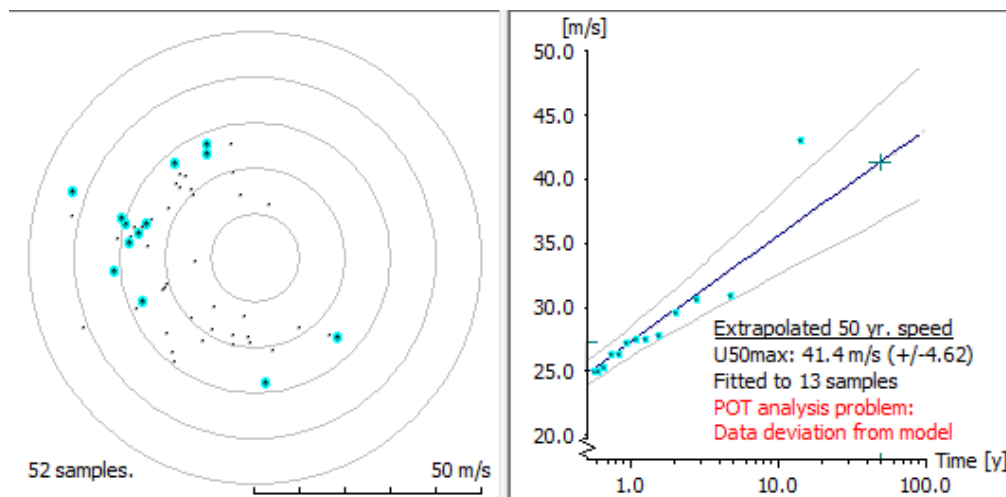

Figure 5.1.2: Observed extreme wind climate applying POT method for the Horns Rev 1 Met mast at 45 m ASL, based on 7-year wind data period

It should be noted that for the AM method $U_{50max,obs}$ is significantly lower if disregarding the 1999 annual maximum. In calculating $U_{50max,obs}$, one of the seven extreme wind samples (AM method) or one of the thirteen samples (POT method) is from the 1999 December storm, which is almost a once in 100-year event, see Figures 5.1.1 and 5.1.2 respectively. Equally weighting this 1999 December sample with the rest few in connection with the use of the Gumbel fitting tends to overestimate $U_{50max,obs}$, especially for the AM method where fewer samples are available.

5.1.2 Predicted extreme wind speeds

$U_{50max,pred}$ for the Horns Rev 1 Met mast at 45 m ASL has been calculated with the SC method applied to the on-site measured wind data and a) the CFDDA long-term reference data from 1985-2005 as well as b) the CFSR long-term reference data from 1979-2011. The calculated $U_{50max,pred}$ applying the SC method to one-year (or shorter) on-site wind data periods are listed in Table 5.1.1.

On-site wind data period	Data recovery rate [%]	Predicted extreme wind speed, $U_{50max,pred}$ [m/s]	
		CFDDA	CFSR
May-Dec 1999	95	37.3 (±2.06)	40.0 (±1.8)
2000	100	38.0 (±2.09)	40.8 (±1.8)
2001	100	37.3 (±2.06)	40.0 (±1.8)
2002	100	37.9 (±2.08)	40.7 (±1.8)
2003	80	37.5 (±2.07)	40.2 (±1.8)
2004	100	37.6 (±2.07)	40.3 (±1.8)
Apr-Dec 2005	100	37.5 (±2.07)	40.1 (±1.8)
Jan-June 2006	99	37.2 (±2.06)	40.0 (±1.8)
Average	-	**37.5**	**40.3**
Standard deviation	-	**0.27**	**0.32**

Table 5.1.1: Calculated $U_{50max,pred}$ (± estimated uncertainty of fitting the Gumbel distribution via PWM [5]), applying SC method, using 1-year datasets for the Horns Rev 1 Met mast at 45 m ASL

For the Horns Rev 1 site, as seen in Table 5.1.1, the SC method tends to give lower values than the POT method; For the CFDDA long-term reference data, the average $U_{50max,pred}$ is 3.9 m/s lower than $U_{50max,obs}$ obtained with the POT method. For the CFSR long-term reference data, the average $U_{50max,pred}$ is 1.1 m/s lower than $U_{50max,obs}$ obtained with the POT method.

Furthermore, one can see that the SC method tends to give the same results, using just one year of measurements, regardless of which year is chosen; the standard deviation of the calculated $U_{50max,pred}$ over the seven separate years is 0.27 m/s and 0.32 m/s for the CFDDA and CFSR data respectively.

For all the one-year (or shorter) on-site wind data periods there is – within the error bars – agreement with the POT method (there is not agreement with the AM method, which in this particular case significantly overestimates $U_{50max,obs}$ for the reason described above).

In connection with the use of reanalysis data to the SC, the Horns Rev 1 site, which represents a nearshore condition, is challenged by the fact that the corresponding reanalysis grid box might contain both land and water. For instance, the corresponding CFDDA grid point for Horns Rev I is only about 5 km from the actual shoreline. The spatial resolution of the CFDDA data is about 40 km. This means that the grid box corresponding to Horns Rev 1 site contains almost half water and half land. This situation corresponds to bigger uncertainty in the generalization approach because a single roughness length needs to be defined to represent this grid box.

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[5] Estimated uncertainty of fitting the Gumbel distribution via probability weighted moments (PWM). Note that the uncertainty of the on-site measured wind data and the uncertainty of the long-term reference wind data are not included.

On the other hand, the corresponding CFSR grid box for Horns Rev 1 is entirely water. This, compared to the CFDDA Horns Rev 1 case, should give smaller uncertainty in the generalization.

The CFDDA winds for the Horns Rev 1 are significantly lower than the CFSR winds. This is partly the reason why the extreme wind from CFDDA is smaller than that from the CFSR data.

Note that in the present implementation of the SC method, WAsP Engineering applies CFDDA long-term reference data only. Therefore, the WAsP Engineering user should be careful when applying the SC method for sites located closer than 20 km to a coastline - especially for offshore/nearshore sites with extreme winds from offshore directions.

Figure 5.1.3 shows two examples of power spectra for wind speeds of a) one-year measured wind data (observed data), b) overlapping 21-year CFDDA data (modelled data) and c) corresponding hybrid. It is seen that with a cross-over frequency of f_c = 0.8 (where there is fine agreement between the spectra), there is a smooth transition of the hybrid spectra from the spectrum of the CFDDA data to the spectra of the measured wind data.
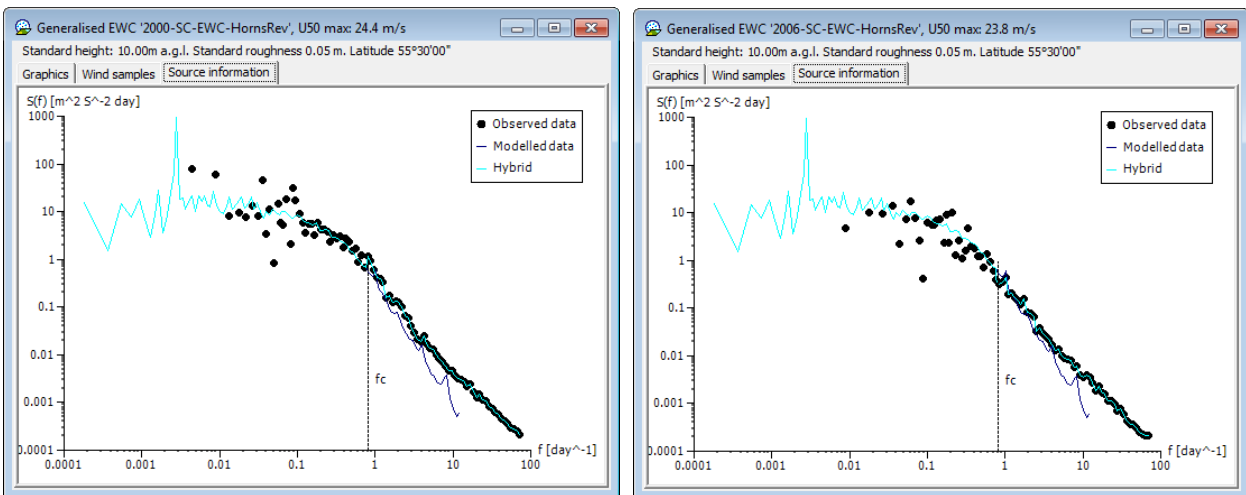

Figure 5.1.3: Power spectra for wind speeds; 1-year measured wind data for 2000 (left) and 2006 (right), 21-year CFDDA data and hybrids

5.2 Høvsøre (Denmark)

5.2.1 Observed extreme wind speeds

For the Høvsøre Met mast at 100 m AGL, the $U_{50max,obs}$ is 42.8 ±3.91 m/s applying the AM method and 46.3 ±2.75 m/s applying the POT method to the entire 10-year on-site wind data period.

The all-sector extreme wind distributions applying the AM and POT methods are seen in Figures 5.2.1 and 5.2.2 respectively. These two figures also show the extreme wind direction distribution for the Høvsøre Met mast at 100 m AGL, indicating that a broad sector from southwest to northwest is the dominant extreme wind direction.
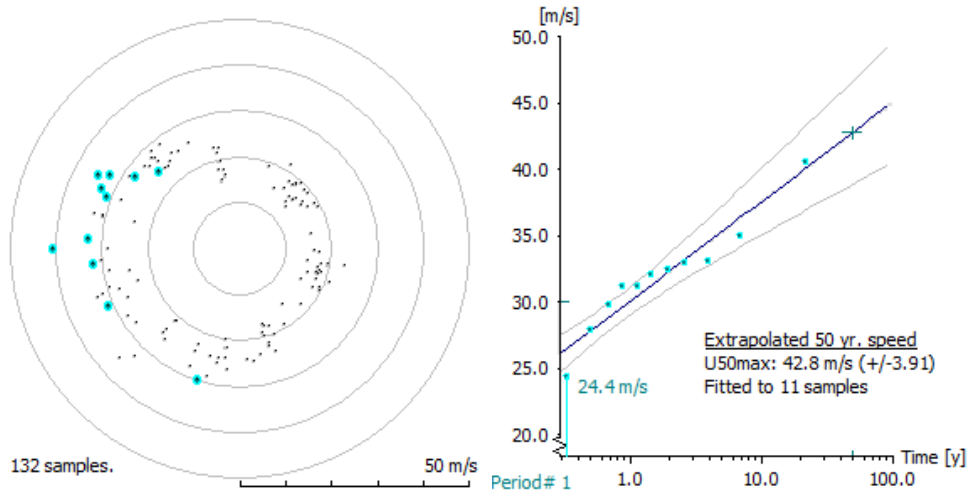

Figure 5.2.1: Observed extreme wind climate applying AM method for the Høvsøre Met mast at 100 m AGL, based on 10-year wind data period
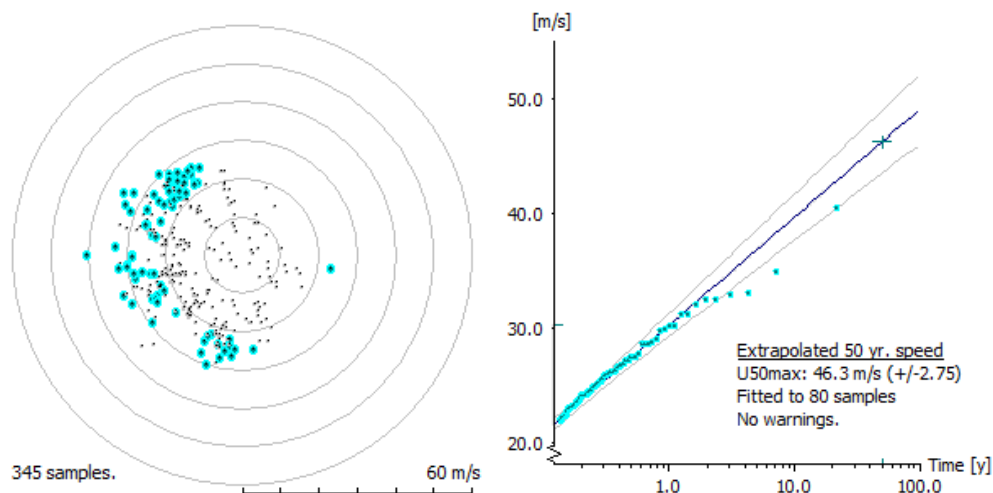

Figure 5.2.2: Observed extreme wind climate applying POT method for the Høvsøre Met mast at 100 m AGL, based on 10-year wind data period

It should be noted that the POT method is quite sensitive to changes in the lower wind speed threshold. In this particular case the default lower wind speed threshold is likely to be too low, leading to a too large number of samples (some of which are not extreme events). Therefore, in this particular case the POT method overestimates $U_{50max,obs}$. However, for the AM and POT methods there is still agreement within the error bars.

5.2.2 Predicted extreme wind speeds

$U_{50max,pred}$ for the Høvsøre Met mast at 100 m AGL has been calculated with the SC method applied to the on-site measured wind data and the CFDDA long-term reference data from 1985-2005. The calculated $U_{50max,pred}$ applying the SC method and using one-year on-site wind data periods are listed in Table 5.2.1.

On-site wind data period	Data recovery rate [%]	Predicted extreme wind speed, $U_{50max,pred}$ [m/s]
2005	96	40.5 (±2.17)
2006	97	40.2 (±2.16)
2007	98	40.8 (±2.18)
2008	98	40.6 (±2.17)
2009	97	40.3 (±2.16)
2010	96	40.2 (±2.16)
2011	93	40.2 (±2.16)
2012	97	40.5 (±2.17)
2013	96	39.9 (±2.15)
2014	97	40.2 (±2.16)
Average	-	**40.3**
Standard deviation	-	**0.26**

Table 5.2.1: Calculated $U_{50max,pred}$ (± estimated uncertainty of fitting the Gumbel distribution via PWM), applying SC method, using 1-year datasets for the Høvsøre Met mast at 100 m AGL

For the Høvsøre site, as seen in Table 5.2.1, the SC method tends to give lower values than the AM method and the POT method: the average $U_{50max,pred}$ is 2.5 m/s lower than $U_{50max,obs}$ obtained with the AM method. However, note that for all the one-year on-site wind data periods there is – within the relatively small error bars – agreement with the AM method (there is not agreement with the POT method, which in this particular case overestimates $U_{50max,obs}$).

Furthermore, one can see that the SC method tends to give the same results, using just one year of measurements, regardless of which year is chosen; the standard deviation of the calculated $U_{50max,pred}$ over the 10 separate years is 0.26 m/s only.

Figure 5.2.3 shows two examples of the power spectra for wind speeds of a) one-year measured wind data, b) overlapping 21-year CFDDA data and c) corresponding hybrid. It is seen that with a cross-over frequency of $f_c = 0.8$ (where is fine agreement between the spectra), there is a smooth transition of the hybrid spectrum from the spectrum of the CFDDA data to the spectrum of the measured wind data.
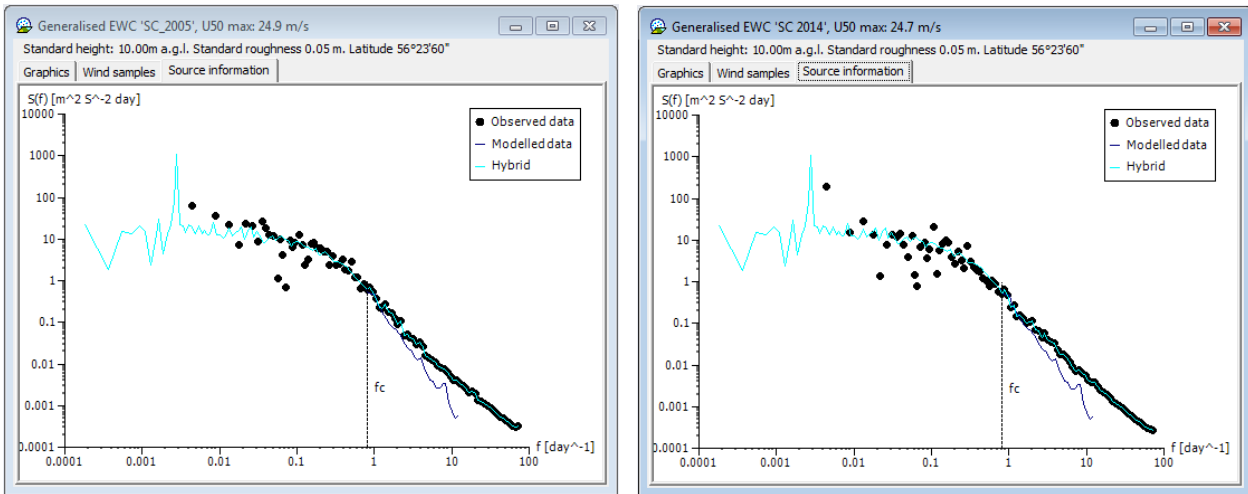
Figure 5.2.3: Power spectra for wind speeds; 1-year measured wind data for 2005 (left) and 2014 (right), 21-year CFDDA data and hybrids

5.3 Sprogø (Denmark)

5.3.1 Observed extreme wind speeds

For the Sprogø Met mast at 70 m AGL, $U_{50max,obs}$ is 33.3 ±1.72 m/s applying the AM method and 34.0 ±1.39 m/s applying the POT method to the entire 22-year on-site wind data period.

The all-sector extreme wind distributions applying the AM and POT methods are seen in Figures 5.3.1 and 5.3.2 respectively. These two figures also show the extreme wind direction distribution for the Sprogø Met mast at 70 m AGL, indicating that a broad sector from southwest to northwest is the dominant extreme wind direction.
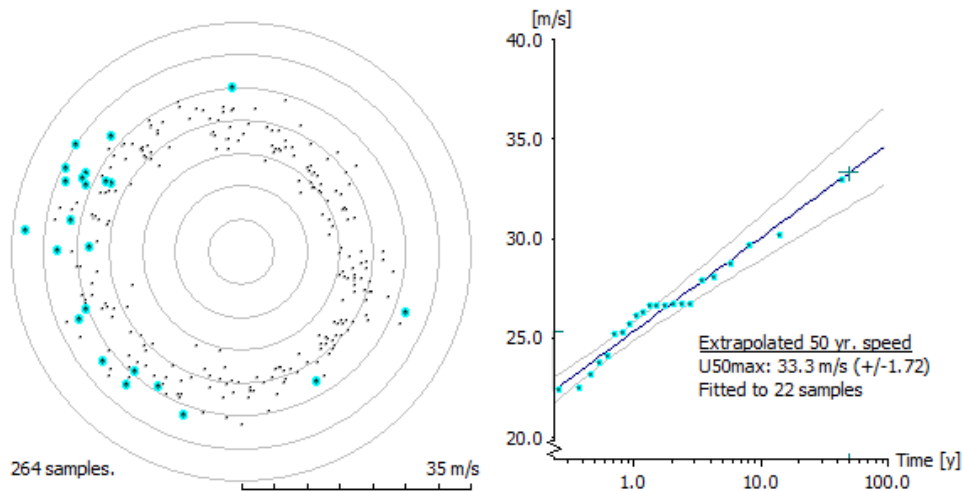

Figure 5.3.1: Observed extreme wind climate applying AM method for the Sprogø Met mast at 70 m AGL, based on 22-year wind data period
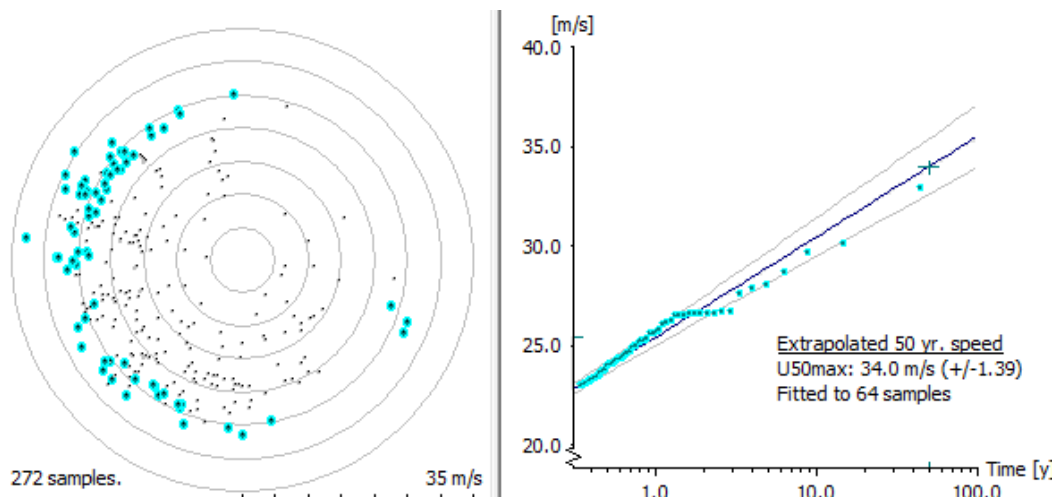

Figure 5.3.2: Observed extreme wind climate applying POT method for the Sprogø Met mast at 70 m AGL, based on 22-year wind data period

5.3.2 Predicted extreme wind speeds

$U_{50max,pred}$ for the Sprogø Met mast at 70 m AGL has been calculated with the SC method applied to the on-site measured wind data and the CFDDA long-term reference data from 1985-2005. The calculated $U_{50max,pred}$ applying the SC method and using one-year (or shorter) on-site wind data periods are listed in Table 5.3.1.

On-site wind data period	Data recovery rate [%]	Predicted extreme wind speed, $U_{50max,pred}$ [m/s]
Sep-Dec 1977	99.9	34.7 (±1.66)
1978	99.9	35.2 (±1.68)
1979	95.9	35.5 (±1.69)
1980	90.5	35.3 (±1.68)
1981	88.5	35.5 (±1.69)
1982	97.1	35.6 (±1.69)
1983	99.9	35.5 (±1.68)
1984	99.9	35.4 (±1.68)
1985	100.0	35.1 (±1.67)
1986	99.9	35.1 (±1.67)
1987	100.0	34.9 (±1.67)
1988	92.5	35.2 (±1.68)
1989	96.5	35.4 (±1.68)
1990	100.0	35.2 (±1.68)
1991	100.0	34.9 (±1.67)
1992	99.4	35.3 (±1.68)
1993	99.9	35.4 (±1.68)
1994	98.9	35.3 (±1.68)
1995	100.0	35.3 (±1.68)
1996	99.7	34.9 (±1.67)
1997	99.8	35.1 (±1.67)
1998	100.0	35.3 (±1.68)
Jan-Sep 1999	100.0	35.1 (±1.67)
Average	**-**	**35.2**
Standard deviation	**-**	**0.22**

Table 5.3.1: Calculated $U_{50max,pred}$ (± estimated uncertainty of fitting the Gumbel distribution via PWM), applying SC method, using 1-year datasets for the Sprogø Met mast at 70 m AGL

For the Sprogø site, as seen in Table 5.3.1, the SC method tends to give somewhat higher values than the AM method and the POT method: the average $U_{50max,pred}$ is 1.9 m/s and 1.2 m/s higher than $U_{50max,obs}$ obtained with the

AM method and the POT method, respectively. Note that for all the one-year (or shorter) on-site wind data periods there is – within the relatively small error bars – agreement with the AM method as well as with the POT method.

Furthermore, one can see that the SC method tends to give the same results, using just one year of measurements, regardless of which year is chosen; the standard deviation of the calculated $U_{50max,pred}$ over the 22 separate years is 0.22 m/s only.

Figure 5.3.3 shows two examples of power spectra for wind speeds of a) one-year measured wind data, b) overlapping 21-year CFDDA data and c) corresponding hybrid. It is seen that with a cross-over frequency of $f_c = 0.8$ (where is fine agreement between the spectra), there is a smooth transition of the hybrid spectra from the spectrum of the CFDDA data to the spectra of the measured wind data.
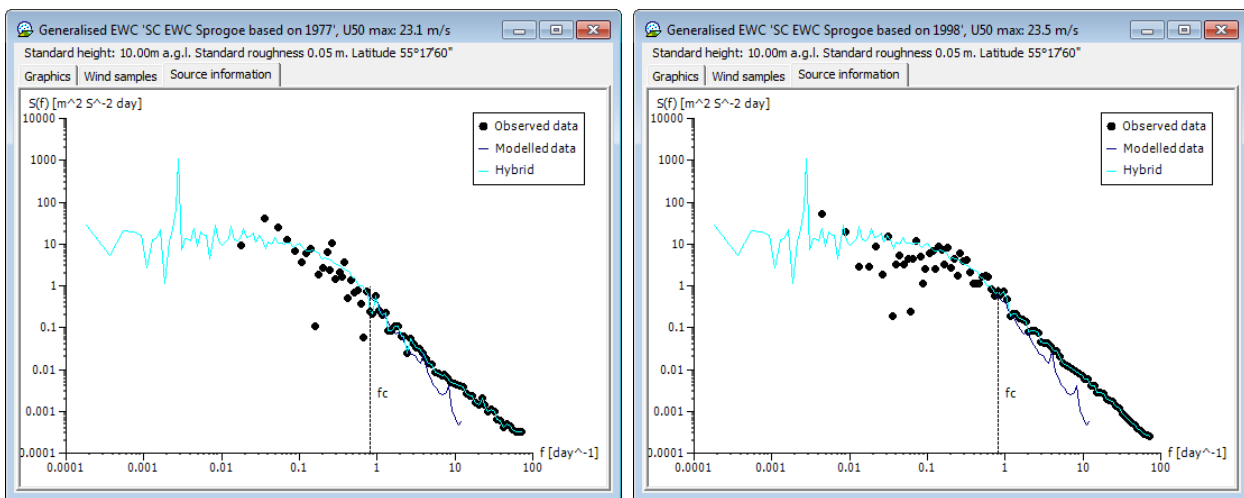

Figure 5.3.3: Power spectra for wind speeds; 1-year measured wind data from 1977 (left) and 1998 (right), 21-year CFDDA data and hybrids

5.4 Tystofte (Denmark)

5.4.1 Observed extreme wind speeds

For the Tystofte Met mast at 39 m AGL, $U_{50max,obs}$ is 32.1 ±1.95 m/s applying the AM method and 31.4 ±1.07 m/s applying the POT method to the entire 32-year on-site wind data period.

The all-sector extreme wind distributions applying the AM and POT methods are seen in Figures 5.4.1 and 5.4.2 respectively. These two figures also show the extreme wind direction distribution for the Tystofte Met mast at 39 m AGL, indicating that a broad sector from southwest to northwest is the dominant extreme wind direction.
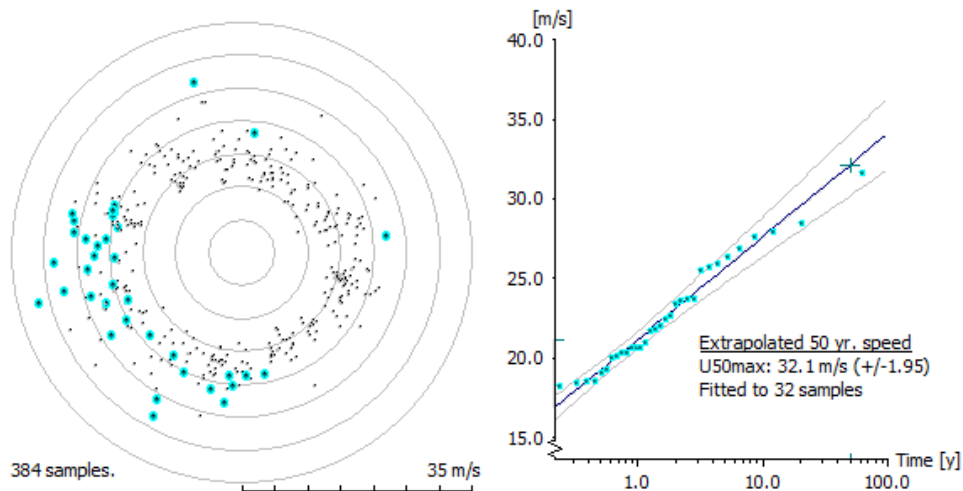

Figure 5.4.1: Observed extreme wind climate applying AM method for the Tystofte Met mast at 39 m AGL, based on 32-year wind data period
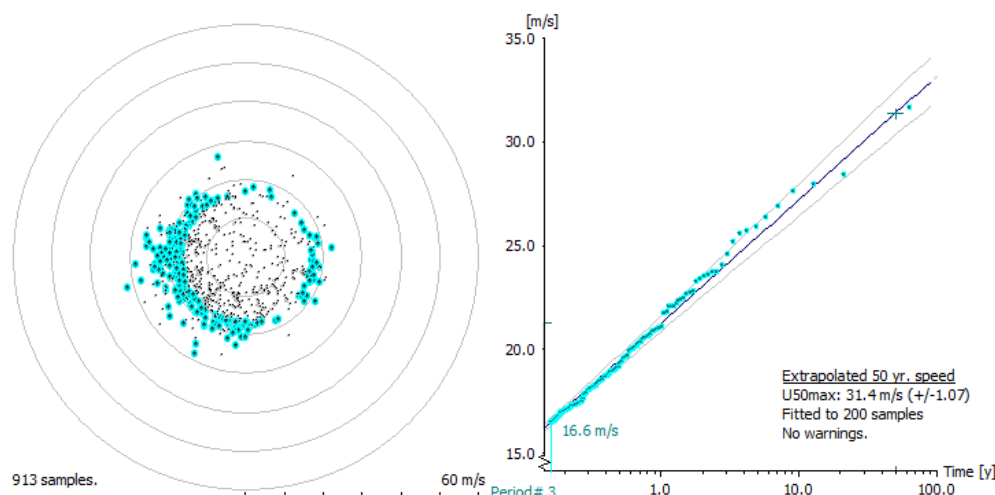

Figure 5.4.2: Observed extreme wind climate applying POT method for the Tystofte Met mast at 39 m AGL, based on 32-year wind data period

5.4.2 Predicted extreme wind speeds

$U_{50max,pred}$ for the Tystofte Met mast at 39 m AGL has been calculated with the SC method applied to the on-site measured wind data and the CFDDA long-term reference data from 1985-2005.

On-site wind data period	Data recovery rate [%]	Predicted extreme wind speed, $U_{50max,pred}$ [m/s]
1983	90	32.1 (±1.74)
1984	100	32.2 (±1.75)
1985	94	32.1 (±1.75)
1986	100	32.3 (±1.76)
1987	99	32.1 (±1.74)
1988	97	32.3 (±1.76)
1989	92	32.3 (±1.75)
1990	92	32.3 (±1.75)
1991	100	32.2 (±1.75)
1992	95	32.4 (±1.76)
1993	100	32.2 (±1.75)
1994	100	32.1 (±1.75)
1995	100	32.2 (±1.75)
1996	96	32.0 (±1.74)
1997	94	32.0 (±1.74)
1998	91	32.1 (±1.74)
1999	99	31.9 (±1.73)
2000	88	31.9 (±1.73)
2001	100	31.9 (±1.73)
2002	78	32.3 (±1.75)
Jan-Nov 2003	96	31.9 (±1.74)
Apr-Dec 2004	95	32.2 (±1.75)
2005	99	32.0 (±1.74)
May-Dec 2006	99	32.0 (±1.74)
2007	99	32.3 (±1.76)
2008	100	32.2 (±1.75)
2009	100	32.1 (±1.74)
2010	96	32.0 (±1.74)
2011	90	32.1 (±1.74)
2012	100	32.1 (±1.74)
2013	100	32.0 (±1.74)
Jan-Oct 2014	100	32.0 (±1.74)
Average	**-**	**32.1**
Standard deviation	**-**	**0.14**

Table 5.4.1: Calculated $U_{50max,pred}$ (± estimated uncertainty of fitting the Gumbel distribution via PWM), applying SC method, using 1-year datasets for the Tystofte Met mast at 39 m AGL

The calculated $U_{50max,pred}$ applying the SC method and using one-year (or shorter) on-site wind data periods are listed in Table 5.4.1.

For the Tystofte site, as seen in Table 5.4.1, the SC method tends to give slightly higher values than the POT method: the average $U_{50max,pred}$ applying the SC method is equal to $U_{50max,obs}$ obtained with the AM method and 0.7 m/s higher than $U_{50max,obs}$ obtained with the POT method. Note that for all the one-year (or shorter) on-site wind data periods there is – within the relatively small error bars – agreement with the AM method as well as with the POT method (maximum difference is 1.0 m/s between a) the SC method using 1992 as on-site wind data period and b) the POT method).

Furthermore, one can see that the SC method tends to give the same results, using just one year of measurements, regardless of which year is chosen; the standard deviation of the calculated $U_{50max,pred}$ over the 32 separate years is 0.14 m/s only.

It is seen in figure 5.4.3 that with a cross-over frequency of $f_c = 0.8$ (where is agreement between the spectra), there is a smooth transition of the hybrid spectra from the spectrum of the CFDDA data to the spectra of the measured wind data. However, please note that the transition of the hybrid spectrum (from the spectrum of the CFDDA data to the spectrum of the measured wind data) is less smooth when using MAY-DEC 2006 as on-site wind data period.
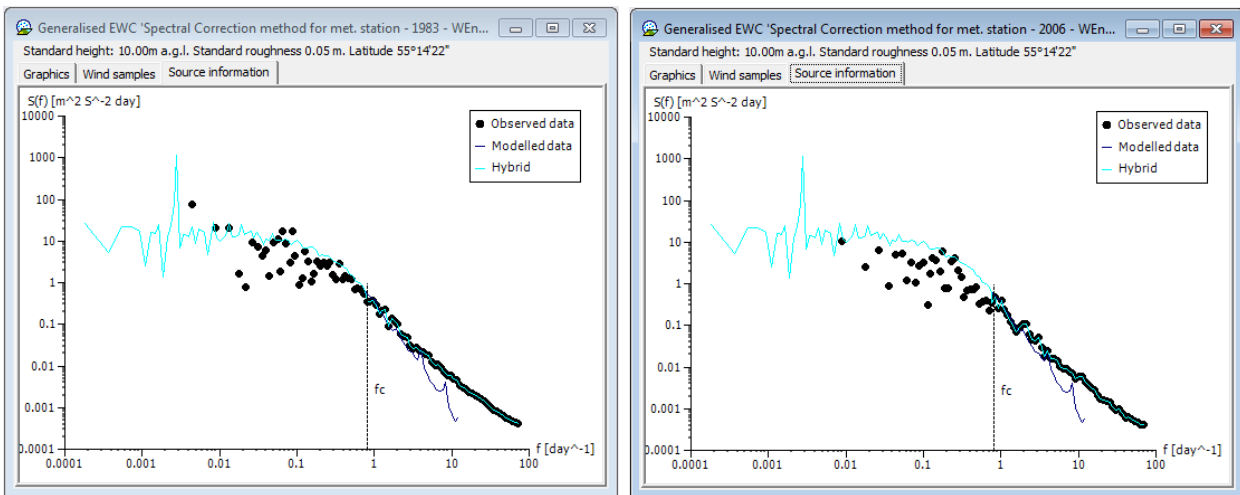

Figure 5.4.3 Power spectra for wind speeds; 1-year measured wind data from 1983 (left) and MAY-DEC 2006 (right), 21-year CFDDA data and hybrids

5.5 Cabauw (Netherlands)

5.5.1 Observed extreme wind speeds

For the Cabauw Met mast at 200 m AGL, $U_{50max,obs}$ is 39.1 ±3.54 m/s applying the AM method and 40.1 ±2.24 m/s applying the POT method to the entire 13-year on-site wind data period.

The all-sector extreme wind distributions applying the AM and POT methods are seen in Figures 5.5.1 and 5.5.2 respectively. These two figures also show the extreme wind direction distribution for the Cabauw mast at 200 m AGL, indicating that a broad sector from southwest to northwest is the dominant extreme wind direction.
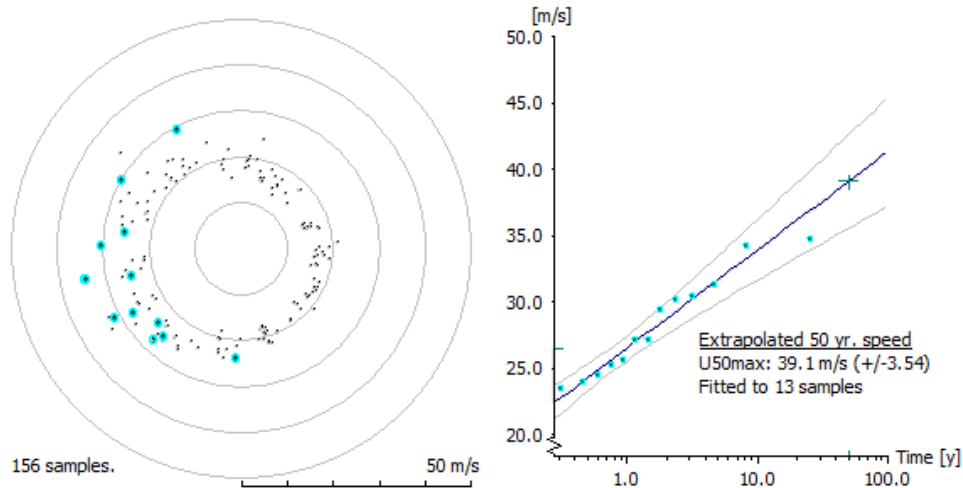

Figure 5.5.1: Observed extreme wind climate applying AM method for the Cabauw Met mast at 200 m AGL, based on 13-year wind data period
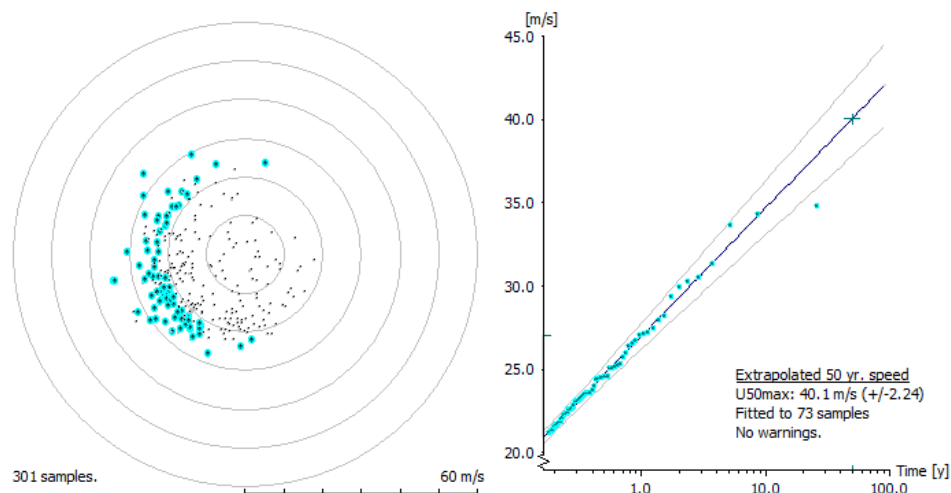

Figure 5.5.2: Observed extreme wind climate applying POT method for the Cabauw Met mast at 200 m AGL, based on 13-year wind data period

5.5.2 Predicted extreme wind speeds

$U_{50max,pred}$ for the Cabauw Met mast at 200 m AGL has been calculated with the SC method applied to the on-site measured wind data and the CFDDA long-term reference data from 1985-2005. The calculated $U_{50max,pred}$ applying the SC method and using one-year on-site wind data periods are listed in Table 5.5.1.

On-site wind data period	Data recovery rate [%]	Predicted Extreme wind speed, $U_{50max,pred}$ [m/s]
2001	100	38.4 (±2.26)
2002	99	38.7 (±2.28)
2003	99	38.9 (±2.29)
2004	98	38.3 (±2.26)
2005	99	38.5 (±2.26)
2006	100	38.5 (±2.27)
2007	99	39.0 (±2.30)
2008	100	38.6 (±2.27)
2009	100	38.3 (±2.25)
2010	98	38.2 (±2.25)
2011	100	38.1 (±2.24)
2012	99	38.1 (±2.28)
2013	100	38.0 (±2.24)
Average	-	**38.4**
Standard deviation	-	**0.30**

Table 5.5.1: Calculated $U_{50max,pred}$ (± estimated uncertainty of fitting the Gumbel distribution via PWM), applying SC method, using 1-year datasets for the Cabauw Met mast at 200 m AGL

For the Cabauw site, as seen in Table 5.5.1, the SC method tends to give slightly lower values than the AM method and the POT method: the average $U_{50max,pred}$ is 0.7 m/s and 1.7 m/s lower than $U_{50max,obs}$ obtained with the AM method and the POT method, respectively. Note that for all the one-year on-site wind data periods there is – within the relatively small error bars – agreement with the AM method as well as with the POT method.

Furthermore, one can see that the SC method tends to give the same results, using just one year of measurements, regardless of which year is chosen; the standard deviation of the calculated $U_{50max,pred}$ over the 13 separate years is 0.30 m/s only.

Figure 5.5.3 shows two examples of power spectra based on one-year measured wind speeds (observed data) and CFDDA (modelled data) and the resulting hybrid spectra (hybrid). It is seen that with a cross-over frequency of f_c = 0.8, the hybrid spectra have a relatively smooth transition from the spectrum of the CFDDA data to the spectra of the measured wind data.
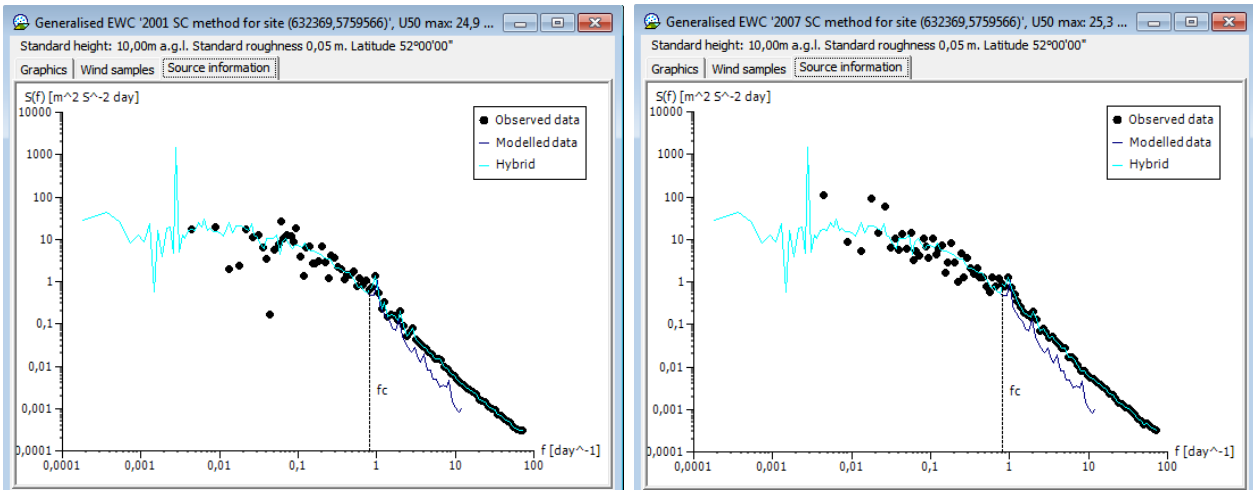
Figure 5.5.3 Power spectra for wind speeds; 1-year measured wind data from 2001 (left) and 2007 (right), 21-year CFDDA data and hybrids

5.6 Champaign (Illinois, USA)

5.6.1 Observed extreme wind speeds

For the Champaign/KCMI Met mast at 10 m AGL, $U_{50max,obs}$ is 22.5 ±1.16 m/s applying the AM method and 23.7 ±0.90 m/s applying the POT method to the entire 18-year on-site wind data period.

The all-sector extreme wind distributions applying the AM and POT methods are seen in Figures 5.6.1 and 5.6.2 respectively. These two figures also show the extreme wind direction distribution for the Champaign/KCMI Met mast at 10 m AGL, indicating that a broad sector from southwest to northwest is the dominant extreme wind direction.
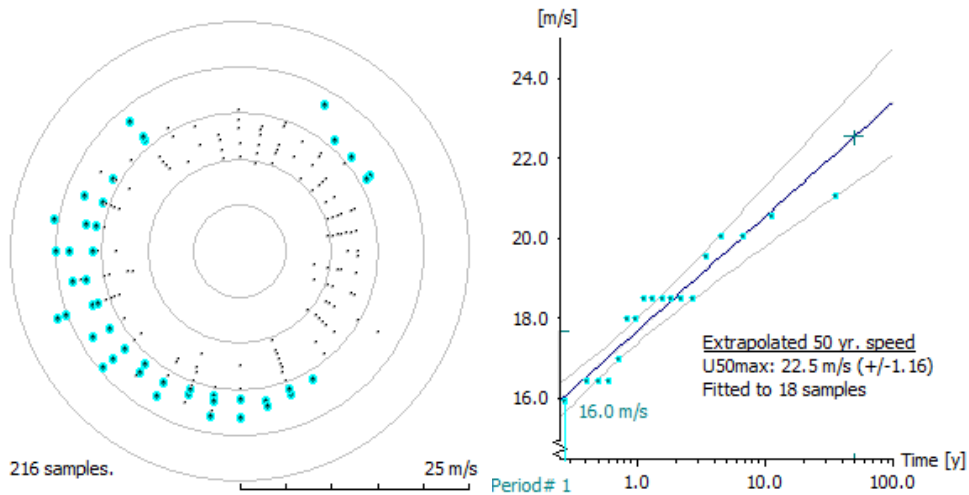

Figure 5.6.1: Observed extreme wind climate applying AM method for the Champaign/KCMI Met mast at 10 m AGL, based on 18-year wind data period
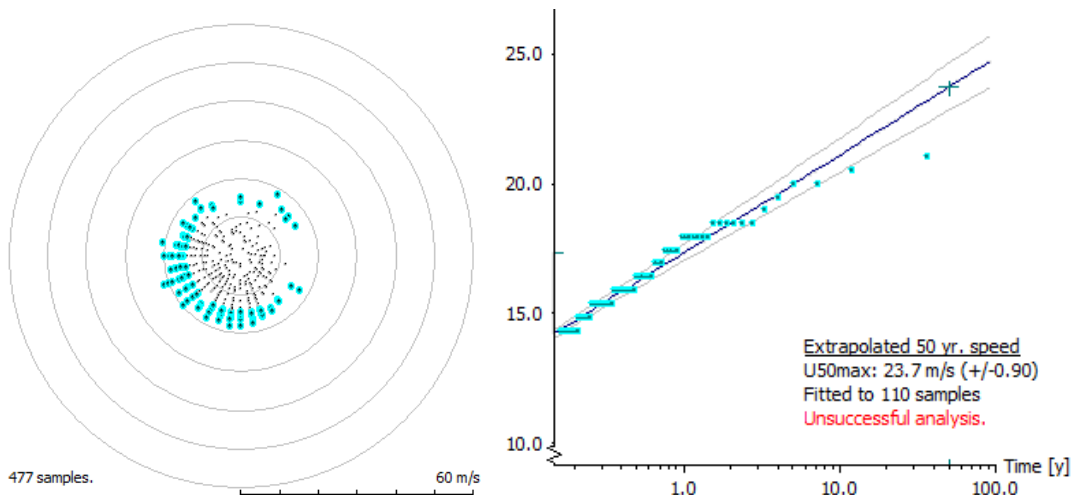

Figure 5.6.2: Observed extreme wind climate applying POT method for the Champaign/KCMI Met mast at 10 m AGL, based on 18-year wind data period

It should be noted that the POT method is quite sensitive to changes in the lower wind speed threshold. In this particular case the default lower wind speed threshold is likely to be too low, leading to a too large number of samples (some of which are not extreme events). Therefore, in this particular case the POT method overestimates $U_{50max,obs}$. However, for the AM and POT methods there is still agreement within the error bars.

5.6.2 Predicted extreme wind speeds

$U_{50max,pred}$ for the Champaign/KCMI Met mast at 10 m AGL has been calculated with the SC method applied to the on-site measured wind data and the CFDDA long-term reference data from 1985-2005. The calculated $U_{50max,pred}$ applying the SC method and using one-year on-site wind data periods are listed in Table 5.6.1.

On-site wind data period	Data recovery rate [%]	Predicted extreme wind speed, $U_{50max,pred}$ [m/s]
1997	70 %	19.8 (±0.84)
1998	70 %	21.5 (±0.91)
1999	70 %	21.8 (±0.93)
2000	71 %	21.9 (±0.93)
2001	73 %	21.6 (±0.92)
2002	93 %	22.1 (±0.94)
2003	87 %	21.8 (±0.92)
2004	73 %	22.1 (±0.94)
2005	70 %	21.7 (±0.92)
2006	74 %	21.8 (±0.93)
2007	72 %	21.8 (±0.93)
2008	68%	22.4 (±0.95)
2009	68%	19.8 (±0.84)
2010	69 %	21.5 (±0.91)
2011	69 %	21.9 (±0.93)
2012	70 %	21.8 (±0.93)
2013	68 %	21.9 (±0.93)
2014	69 %	19.9 (±0.84)
Average	**-**	**21.5**
Standard deviation	**-**	**0.80**
2001-2003	84 %	21.5 (±0.91)

Table 5.6.1: Calculated $U_{50max,pred}$ (± estimated uncertainty of fitting the Gumbel distribution via PWM), applying SC method, using 1-year datasets, and highest-recovery 3-year set for the Champaign/KCMI Met mast at 10 m AGL

For the Champaign site, as seen in Table 5.6.1, the SC method tends to give slightly lower values than the AM method. The average $U_{50max,pred}$ is 1.0 m/s lower than $U_{50max,obs}$ obtained with the AM method, but just within the range of the (mean) statistical uncertainty, which on average was 0.91 m/s (with the latter deviating by ~5 % from case to case). For most of the one-year (or shorter) on-site wind data periods there is – within the relatively small error bars – agreement with the AM method (there is not agreement with the POT method, which in this particular case overestimates $U_{50max,obs}$).

Furthermore, one can see that the SC method tends to give the same results, using just one year of measurements, regardless of which year is chosen; the standard deviation of the calculated $U_{50max,pred}$ over the 18 separate years is 0.80 m/s.

Note that for continental climates such as that at the Champaign site, for some years the SC method can give substantially smaller estimates of $U_{50max,pred}$ than the AM or POT methods; this is evident when one looks at the results for 1997 and 2014. The primary reason for this is the presence of repeated downburst families ('derechos'), which can occur for several hours and up to several times per year in such climates. These types of events do not

explicitly satisfy the Rice theory implicit within the SC method because they are not turbulence, but nature tends to convert such events into turbulence – particularly as the ground is approached; however, they can also be lacking from reanalysis (or even mesoscale) model data. The spectra are not severely impacted (particularly e.g. here at a 10 m observation height), and the SC method remains robust.

Figure 5.6.3 shows four examples of power spectra for wind speeds of one-year measured wind data, overlapping 21-year CFDDA data, and corresponding hybrid spectrum, for selected years at KCMI. It is seen that with a cross-over frequency of $f_c = 0.8$, there is a smooth transition of the hybrid spectra from the spectrum of the CFDDA data to the spectra of the measured wind data for some years (e.g. 2008), but not others (e.g.1997 and 2014). It could be argued that different f_c should be used in the latter cases, as one can see in Figure 5.6.3: where the matching occurs can dictate the amplitude of the variance (i.e. area under the hybrid spectrum curve). Indeed in cases lacking a well-matched transition such as 1997 and 2014, the SC method can give a substantially different estimate of $U_{50max,pred}$ than the $U_{50max,obs}$ obtained with the AM and POT methods.
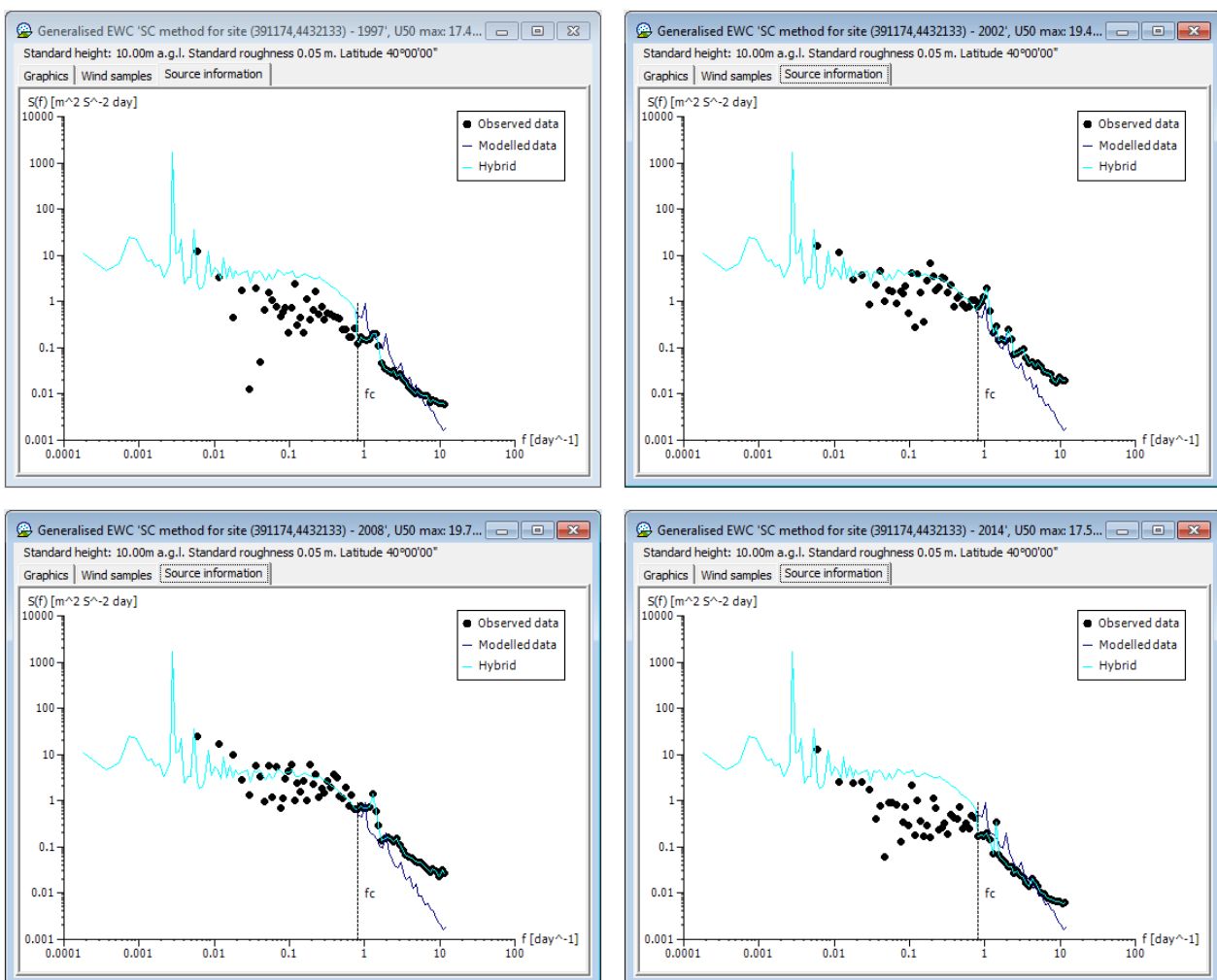

Figure 5.6.3: Power spectra for wind speeds; 1-year measured wind data from 1997 (top left), 2002 (top right), 2008 (bottom left) and 2014 (bottom right), 21-year CFDDA data and hybrids

Note from the Gumbel plot in Figure 5.6.2 (right) that the derecho events tend to give a smaller-sloped line (and thus smaller α and subsequently smaller fitting uncertainty) than the line implied by the points for smaller return periods. I.e., this might be considered a mixed climate, and in this case the U_{50max} value is reduced by fitting to one 'extreme climate' (cluster of points) versus another. One way around this may be to use the SC method in conjunction with the AM method and/or the POT method, whereby e.g. a more conservative value could be estimated. Another possibility is comparison with mesoscale time-series; both of these fall within the bounds of ongoing research at DTU Wind Energy.

6 Conclusion

The Spectral Correction (SC) method for calculating extreme winds has recently been integrated in the *WAsP Engineering* software package. For the SC method, there is no need for the WAsP Engineering user to provide any *long-term* wind data in order to generate an observed extreme wind climate. Instead, WAsP Engineering uses CFDDA long-term reference wind data, which is made available by DTU Wind Energy on a computer server in the cloud[6].

The accuracy of the SC method has been validated by comparing predicted extreme wind speeds (SC method) to observed extreme wind speeds (AM method and POT method). For each of six sites[7], it is seen that when applying the SC method to a number of one-year on-site wind data periods, the predicted extreme wind speeds are – within the error bars – in agreement with the observed extreme wind speeds. Also, the average of the predicted extreme wind speeds is within 3.9 m/s lower (Horns Rev 1) and 1.9 m/s higher (Sprogø) than the observed extreme wind speeds. Therefore, except for the offshore Horns Rev 1 site (where the proximity to the shoreline is a problem) the SC method is quite accurate when applied to one-year on-site wind data periods.

The consistency of the SC method has been validated by checking the standard deviations of predicted extreme wind speeds (SC method only). For each of six sites, it is seen that when applying the SC method to a number of one-year on-site wind data periods, the standard deviations of the predicted extreme wind speeds are within 0.82 m/s (Champaign), i.e. very low. Therefore, for all six sites the SC method is very consistent when applied to one-year on-site wind data periods.

Note that a significant bias in the results can be introduced at some sites, by adjusting the roughness length of the terrain map used. Therefore, we do caution that the WAsP Engineering user must take care with properly modelling the terrain surface roughness.

Note also that the WAsP Engineering user should be careful when applying the SC method for sites located closer than 20 km to a shoreline - especially for offshore/nearshore sites with extreme winds from offshore directions.

For each of six sites, it is seen that with a cross-over frequency of $f_c = 0.8$, there is in most cases a smooth transition of the hybrid spectrum from the spectrum of the reanalysis data to the spectrum of the measured wind data. Therefore, WAsP Engineering applies $f_c = 0.8$ as a default value.

In cases lacking a well-matched transition of the hybrid spectrum, the SC method can give a substantially different estimate of the extreme wind speed than the extreme wind speeds obtained with the AM method and/or the POT method. Particularly for continental climates, the SC method can for some one-year on-site wind data periods give substantially smaller estimates of predicted extreme wind speeds.

We recommend that the WAsP Engineering user should always check the transition of the hybrid spectrum (from the spectrum of the reanalysis data to the spectrum of the measured wind data).

Finally, the WAsP Engineering user should use the SC method in conjunction with the AM method and/or the POT method, whereby e.g. a more conservative extreme wind could be calculated.

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[6] At release, the data cover Europe (incl. Turkey) and the USA. DTU Wind Energy will gradually expand coverage and global coverage is expected in 2017.

[7] Three (of twelve) observed extreme wind speeds are disregarded, i.e. the AM method for the Horns Rev 1 site, the POT method for the Høvsøre site and the the POT method for the Champaign site.

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National Center for Atmospheric Research

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Appendix: Extreme wind atlas for South Africa

The Spectral Correction (SC) method has been applied to create the extreme wind atlas for South Africa and validated by measurements (Larsén and Kruger 2014). The two figures below show the maps of the extreme 1-hour average wind speed with a recurrence period of 50 years at 10 m, over a roughness length of 5 cm over South Africa, obtained from standard meteorological measurements of wind speed and direction from 76 stations across the country and CFSR data with the SC method, respectively.

The spatial distribution as well as the magnitude of the 50-year wind are comparable between the measurements and the one from CFSR data with the SC method.
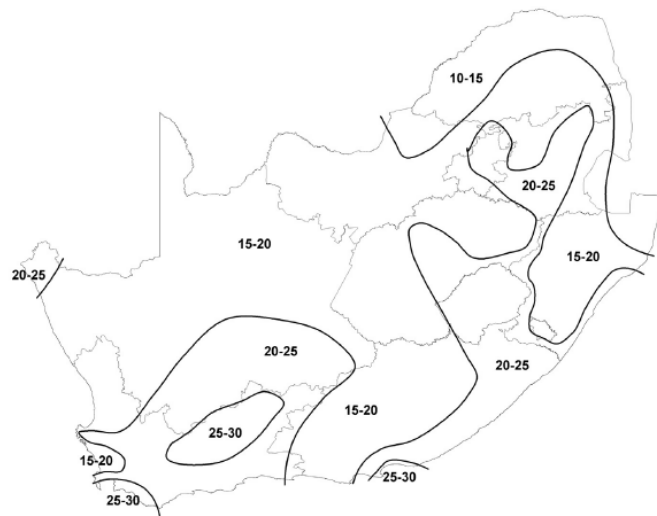

Figure: The atlas of the 50-year wind (m/s) at 10 m, over roughness length of 5 cm, for South Africa using standard meteorological measurements, one-hour resolution (from Kruger et al. 2011)
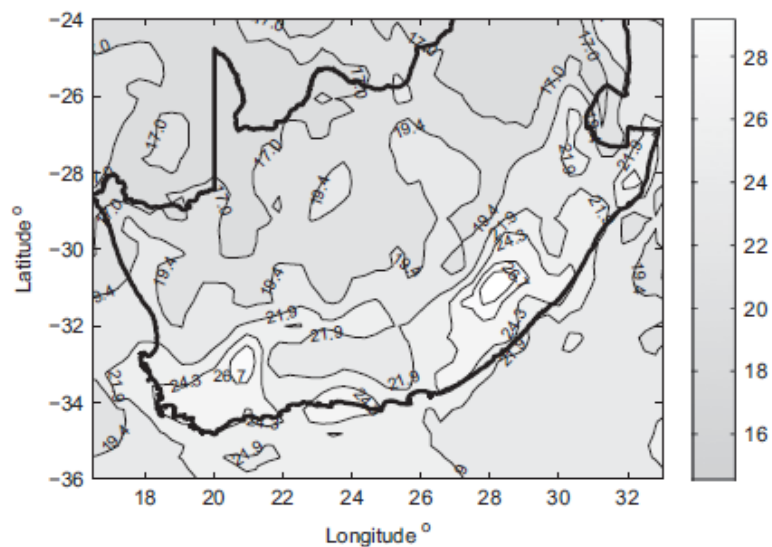

Figure: The atlas of the 50-year wind (m/s) at 10 m, over roughness length of 5 cm, for South Africa using CFSR data and the SC method, one-hour resolution (from Larsén and Kruger 2014)

DTU Wind Energy is a department of the Technical University of Denmark with a unique integration of research, education, innovation and public/private sector consulting in the field of wind energy. Our activities develop new opportunities and technology for the global and Danish exploitation of wind energy. Research focuses on key technical-scientific fields, which are central for the development, innovation and use of wind energy and provides the basis for advanced education at the university.

We have more than 240 staff members of which approximately 60 are PhD students. Research is conducted within nine research programmes organized into three main topics: Wind energy systems, Wind turbine technology and Basics for wind energy.