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Extreme Wind Calculation Applying Spectral Correction Method - Test and Validation

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Abstract

We present a test and validation of extreme wind calculation[1] applying the Spectral Correction (SC) method as implemented in a DTU Wind Condition Software. This method can do with a short-term (~1 year) local measured wind data series in combination with a long-term (10-20 years) reference modelled wind data series like CFSR and CFDDA reanalysis data for the site in question.

The validation of the accuracy was performed by comparing with estimates by the traditional Annual Maxima (AM) method and the Peak Over Threshold (POT) method, applied to measurements, for six sites: four sites located in Denmark, one site located in the Netherlands and one site located in the USA, comprising both on-shore and off-shore sites. The SC method was applied to 1-year measured wind data while the AM and POT methods were applied to long-term measured wind data. Further, the consistency of the SC method was validated from the variance of the extreme wind prediction when different years are used as the period of the short-term measured wind data.

For all six sites, the SC method was found to be quite accurate and very consistent when applied to one-year on-site wind data periods.

It is concluded that the SC method in combination with widely available long-term reference data is a valid alternative to estimate extreme winds in cases where only short-term on-site measured wind data are available.

1 Background

Traditional extreme wind estimation using methods like the Annual Maxima (AM) method [6] and the Peak-over-Threshold (POT) method [7], [5] (also called the Method of Independent Storms) applied to measured wind data suffer from the draw-back that a not-too-small number of years of wind data are required to provide an estimate with a reasonable reliability. Thus for the AM method typically 10 years of measured wind data or more is needed, for the POT method may be somewhat smaller [5]. However, in the exploration for suitable wind farm sites often only 1 or two years of measured wind data are available and consequently extreme wind estimation will be very uncertain. The SC method aims to solve this problem.

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[1] In this context, the extreme wind 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).

Thus, in addition to the AM and the POT methods, the SC method has been implemented in a *DTU Wind Condition Software*.

2 The Extreme Wind Estimation Methods

2.1 The Annual Maxima and Peak-Over-Threshold methods

For reference we briefly present the AM and POT methods.

The AM method [6] is based on the Gumbel double-exponential extreme value cumulative distribution for fitting 1-year extreme wind speeds, i.e. annual maximum-winds:

$$F(U') = \exp\left(-\exp\left(-\frac{U'-\beta}{\alpha}\right)\right) \qquad \text{(Eq.2.1.1),}$$

where $F(U')$ is the probability that the wind speed U' is not exceeded during one year, α and β are distribution parameters. For a T-year return time, T>>1 year, the extreme wind estimate is then

$$U_T = \alpha \ln T + \beta \qquad \text{(Eq.2.1.2).}$$

The distribution parameters α and β may be determined by an analytical method, but visually the determination may be thought of as fitting a straight line with slope α to the ranked set of n annual-maximum winds $U_i^{\max}$ (i.e. sorted in ascending order) versus a “logarithmic- pseudo-time” of $-\ln\left(-\ln\left(\left(i-\tfrac{1}{2}\right)/n\right)\right)$ as illustrated in fig. 2.1.1.

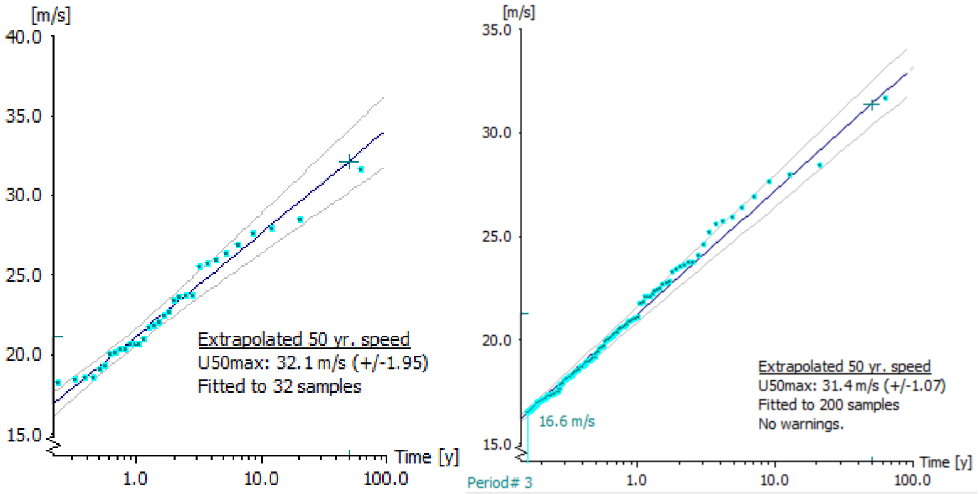

Figure 2.1.1: Left: Observed extreme wind climate applying AM method for the Tystofte Met mast at 39 m AGL, based on 32-year wind data period. The Gumbel straight-line fit to ranked annual maximum winds is seen. Right: Same, but applying the POT method.

The statistical uncertainty of the AM extreme wind estimate $\sigma(U_T)$ may be shown to be proportional to α and, in effect, inversely proportional to the square root of observation years for the set of extreme winds.

The Peak-Over-Threshold method [7] is based on the expression for the so-called exceedance rate. i.e. the number of observed wind speed peaks exceeding a certain speed-threshold U_{thresh} per unit time

$$\lambda(u) = \lambda_0 \exp(-\frac{u - U_{thresh}}{A}) \qquad \text{(Eq. 2.1.3)}$$

The corresponding extreme wind estimate for a return-time T_{ret} is

$$u_{extr}(T_{ret}) = U_{thresh} + A \ln(\lambda_0 T_{ret}) \qquad \text{(Eq. 2.1.4)}$$

The distribution parameters A and λ_0 may be found analytically from a set of wind speed peaks within a certain time-range T_{obs} (years) but could also be thought of as fitting a straight line with slope A to the wind speed peaks but ranked in ascending order, $V_i^{\max}$, i=1..n, versus a "logarithmic-pseudo-time" of $\ln\left(T_{obs}/(n-i+½)\right)$ as also illustrated in fig. 2.1.1.

2.2 Theory of Spectral Correction method

The SC method was developed by Larsén et al. [4] 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. [4], this smoothing effect was shown as the tapered power spectrum in the mesoscale range, reflecting the missing wind variability in the mesoscale model results for scales connected with (temporal) frequencies of about 2 day^{-1} and higher as illustrated for the WRF mesoscale model in Figure 2.1.

The core of the SC 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 2.1).

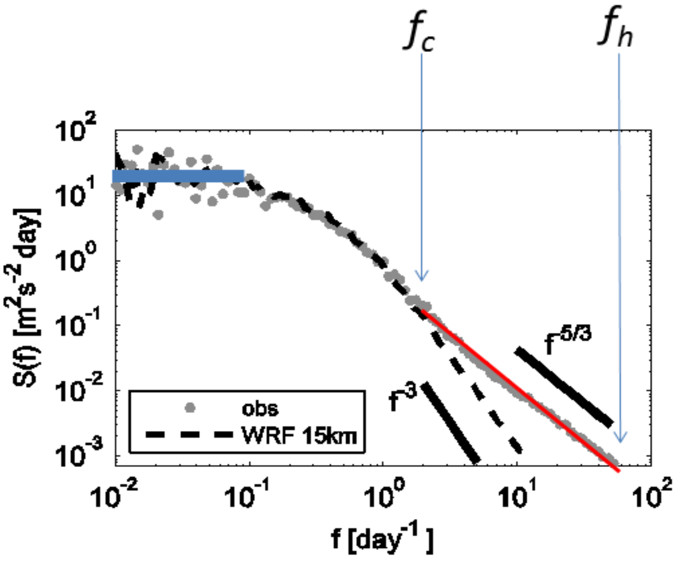

Figure 2.1: Characterizing the power spectrum of wind speed – case study for the offshore Horns Rev site. Red line: spectrum model $S(f) = a f^{-5/3}$ for the range f_c .. f_h

The resulting hybrid spectrum is seen to fulfil the following natural requirements:

- The spectrum of the low frequency part satisfies *dS(f)/df* → 0 as *f* → 0 (thick blue line in fig. 2.1), a sign of (semi-) stationarity of the time series
- The spectrum has a slope of -5/3 in the high-frequency range (from of about 2 day^{-1}) as expected from theory and measurements [12].
- Smooth transition at fc from modelled to observed spectrum

In principle this method can be applied to measurement series as short as a few months. The details of the derivation of the algorithms related to this method can be found in Larsén et al. [4]. Briefly, Larsén et al. establishes a relation between extreme wind occurrence and power spectrum of a wind time series by assuming that the once-per-year exceedance follows a Poisson process and can be simplified as a Gaussian process. Thus the T_0 (T_0 =1 year) extreme wind, $\overline{U}_{\max}$, was derived to depend on the zero- and second-order spectral moments, m_0 and m_2 , and the mean wind speed $\overline{U}$ as

$$\frac{\overline{U}_{\max} - \overline{U}}{\sigma} = \sqrt{2\ln\left(\frac{1}{2\pi}\sqrt{\frac{m_2}{m_0}}T_0\right)}, \sigma = \sqrt{m_0}, m_j = 2\int_0^{\infty} \omega^j S(\omega)d\omega, \qquad \text{(Eq. 2.2.1)}$$

Here *S*(*ω*) is the power spectrum of the wind speed, *ω* = 2*πf.* Eq. 2.2.1 may then be applied to both the modelled spectrum from a reanalysis data series - like CFDDA [1] or CFSR [2],[3] - and the hybrid spectrum to get a measure for the effect of including the observed high-frequency part of the power spectrum.

It was found that the measured time series should be at least several months long, and the recovery rate should preferably be 90% or better. Bad data or gaps could be deleted or, for shorter randomly distributed gaps, filled in with linear interpolation.

2.3 Calculating Spectral Correction extreme wind climate

From the modelled spectrum and the hybrid spectrum, a spectral correction factor is calculated:

$F_{SC} = \frac{\overline{U_{\max}^{Hybrid}}}{\overline{U_{\max}^{Mod}}}$, where $\overline{U_{\max}^{Mod}}$ and $\overline{U_{\max}^{Hybrid}}$ are the means of the annual maximum winds calculated from the modelled spectrum and the hybrid spectrum, respectively. The spectral-corrected annual maximum winds, forming the SC method extreme wind climate, are then found as

$U_{1y-\max;i}^{SC} = F_{SC} U_{1y-\max;i}^{Mod}$, where $U_{1y-\max;i}^{Mod}$ is maximum wind speed of the i$^{\text{th}}$ year of the modelled time series and $U_{1y-\max;i}^{SC}$ the corresponding spectral corrected annual max wind.

3 Implementation of Extreme Wind estimation in DTU Wind Condition Software

The DTU Wind Condition Software uses a combined flow model consisting of the linear flow model LINCOM [10], which like the well-known WAsP software is based on the Jackson-Hunt-based flow model [11], in combination with the so-called geostrophic drag-law.

The combined flow model is used to transform extreme wind data (and other wind data) from an observation point to Generalized Wind Climate at standard conditions defined as flat terrain with uniform surface roughness; and from Generalized Wind Climate to any particular target sites, typically wind turbine positions, thus e.g. obtaining the 50-year extreme wind. Detailed terrain representations – maps of elevation and roughness lengths – must be supplied for the surroundings of observation points and target sites. For water surfaces the model itself estimates the roughness length in dependence of wind speed and fetch to the nearest upwind shore. The DTU Wind Condition Software has both AM and POT extreme wind estimation implemented using the above described procedure.

In addition, the SC method for calculating extreme winds (e.g. U_{50}^{max}), as described in section 2, has recently been integrated into the DTU Wind Condition Software – a somewhat more complicated integration procedure than for the AM and the POT methods because the generation of the generalized SC extreme wind climate involves a number of steps. However, once this has been carried out the procedure to generate the corresponding extreme wind estimate at a target site is straight forward, following the same methodology as for the AM and POT methods.

3.1 Generation of Generalized SC Extreme Wind Climate

Generating a generalized SC extreme wind climate involves three steps:

- Generalization of long-term reference wind data from reanalysis data (CFDDA [1] or CFSR [2],[3]). This is performed in a pre-process, using the same combined flow model as in LINCOM but in combination with a mesoscale terrain description[2] around the reanalysis grid-point. The resulting generalized CFDDA time series have been saved in an internet-database, whereas generalized CFSR-data have only been created when needed[3].

- Generalization of on-site measured wind data. This is performed in the Wind Condition Software as described above using a detailed terrain map, containing elevation and roughness features around the observation point.

- Calculation of generalized extreme wind climate, using the procedure described in sections 2.2 and 2.3, 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.

The uncertainty of the SC method has several sources of which the important ones specific for the SC method are a) the uncertainty of the roughness length used when generalizing the modelled long-term reference wind data; and b) the choice of modelled data. Another important source, but shared with the AM and POT methods is c) the uncertainty related to the Gumbel-fitting of the extreme wind data.

The sensitivity of the generalized wind speed to roughness was analysed by Kelly & Jørgensen [9] and implicitly by Badger et al. [8], §6. They found that the corresponding uncertainty should be taking into account; e.g. roughness lengths too large by an order of magnitude could cause wind speeds to be overpredicted by approximately 30 % or more (depending on the actual roughness).

The only quantifiable source of uncertainty is the straight-line Gumbel-fitting of extreme events (section 2.1). As explained in section 2.1, this depends basically on the ratio of the Gumbel-

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[2] A Terrain description consistent with the mesoscale calculation used to produce the reanalysis data. For off-shore grid points the roughness length was derived from the wind profile available at the reanalysis grid point (CFDDA) or from the speed- and fetch-dependent roughness model of LINCOM (CFSR).

[3] It showed out that it would be more difficult to get appropriate surface roughness lengths for CFSR data than for CFDDA; thus only generalized CFDDA data were saved in an internet-database.

slope (α) to the square-root of years of the covered time series, so it is reduced when using the long time series of reanalysis data.

4 Results

This section presents the results of extreme wind calculations applying the SC method in comparison with the AM and POT methods, 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, using a DTU Wind Condition Software (section 3).

For each of the six sites also a number of *predicted* extreme wind speeds, $U_{50max,pred}$, have been calculated by applying the SC method to the of one-year periods of wind data from the on-site met mast, one by one, as described in section 3, using the DTU Wind Condition Software.

The six sites, comprising off-shore as well as on-shore locations, are

Name	**Location**	**Off/On-shore**	**Height**
Horns Rev 1	North Sea, Denmark	Off-shore	45 m ASL
Hoevsoere	W. Jutland, Denmark	On-shore	100 m AGL
Sprogoe	Great Belt, Denmark	Off-shore	70 m ASL
Tystofte	Zealand, Denmark	On-shore	39 m AGL
Cabauw	Rotterdam, Netherland	On-shore	200 m AGL
Champaign	Illinois, USA	On-shore	10 m AGL

The results of the comparative estimations are shown in figures 4.1 to 4.6 with plot of spectra in the left part and extreme wind calculation comparisons in the right part. The results are summarized in table 4.1. The SC extreme wind estimations were performed using CFDDA long-term reference wind data if not otherwise stated.

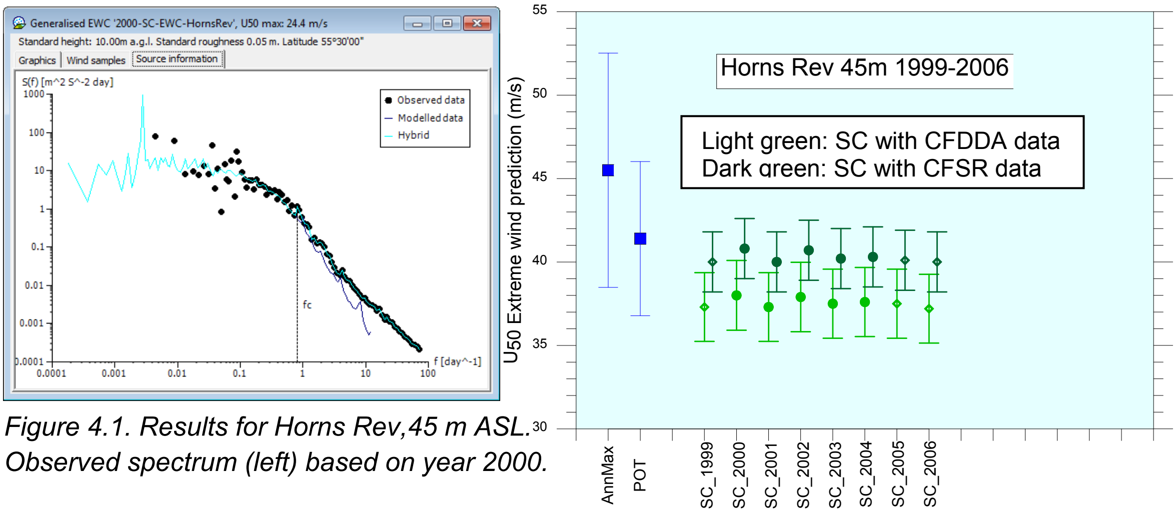
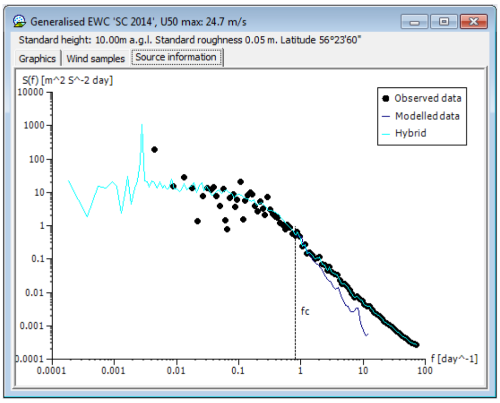


Figure 4.1. Results for Horns Rev,45 m ASL. Observed spectrum (left) based on year 2000.



Generalised EWC 'SC 2014', U50 max: 24.7 m/s

Standard height: 10.00m a.g.l. Standard roughness 0.05 m. Latitude 56°23'60"

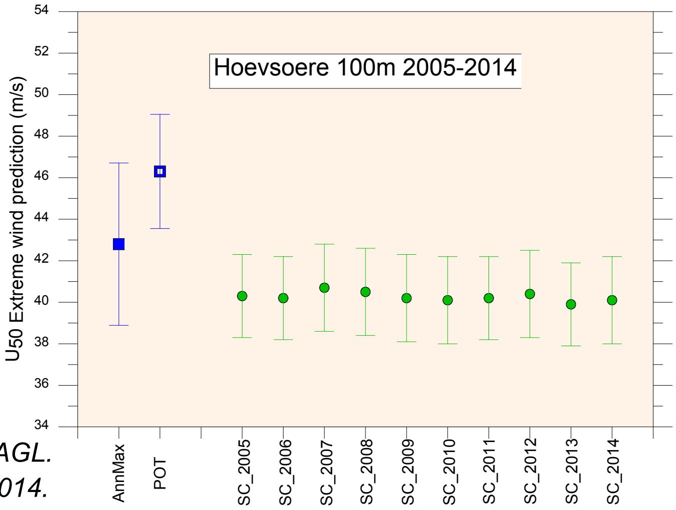
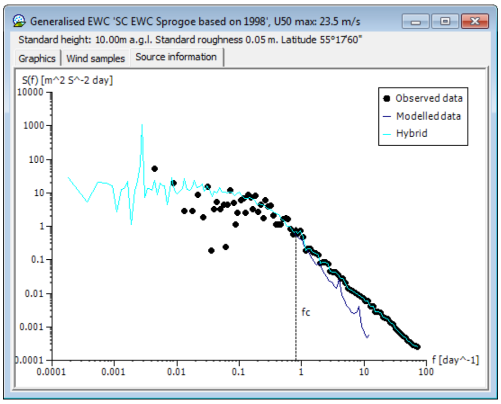


Figure 4.2. Results for Hoevsoere,100 m AGL. Observed spectrum (left) based on year 2014.



Generalised EWC 'SC EWC Sprogoe based on 1998', U50 max: 23.5 m/s

Standard height: 10.00m a.g.l. Standard roughness 0.05 m. Latitude 55°17'60"

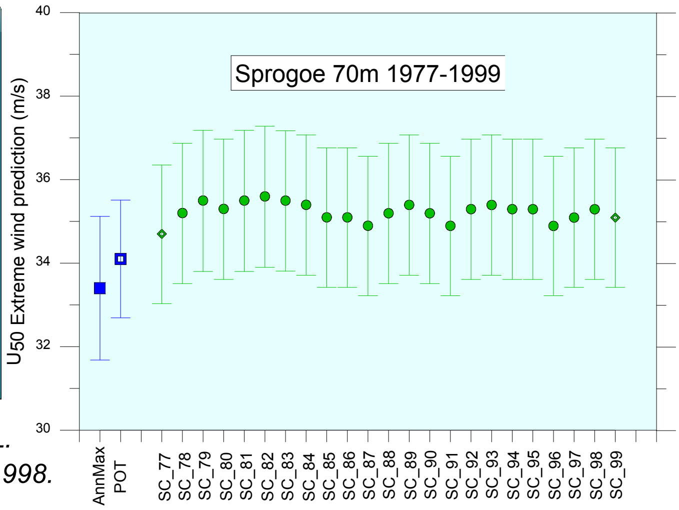
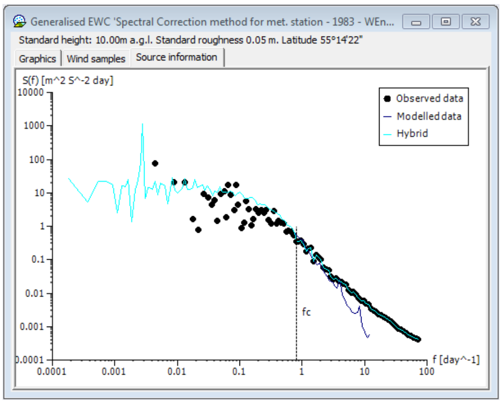


Figure 4.3. Results for Sprogoe,70 m ASL. Observed spectrum (left) based on year 1998.



Generalised EWC 'Spectral Correction method for met. station - 1983 - WEn...

Standard height: 10.00m a.g.l. Standard roughness 0.05 m. Latitude 55°14'22"

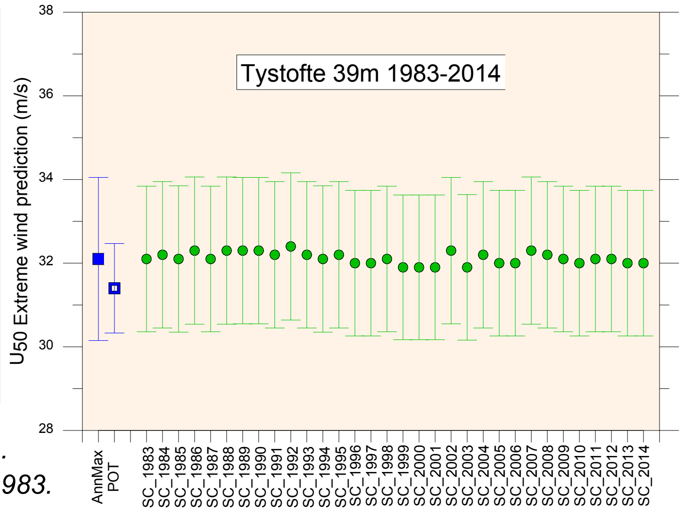
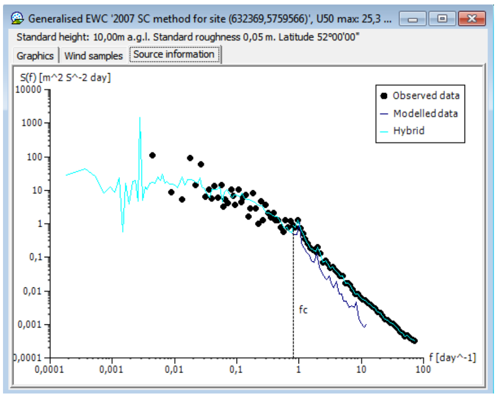


Figure 4.4. Results for Tystofte,39 m AGL. Observed spectrum (left) based on year 1983.



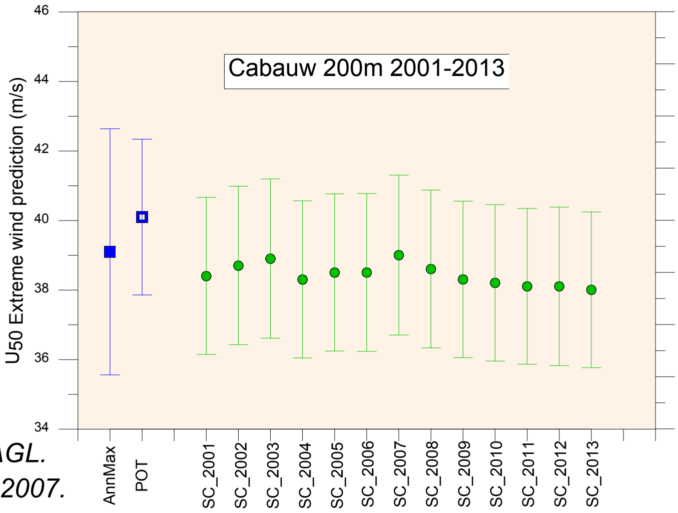
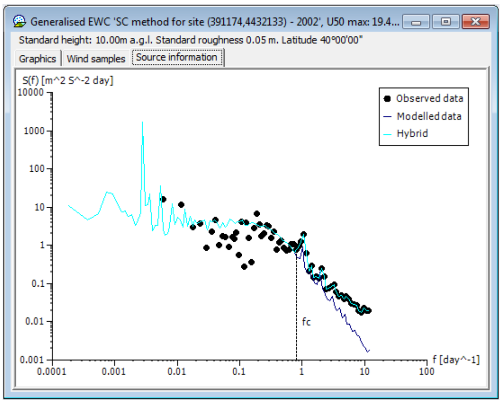


Figure 4.5. Results for Cabauw, 200 m AGL. Observed spectrum (left) based on year 2007.



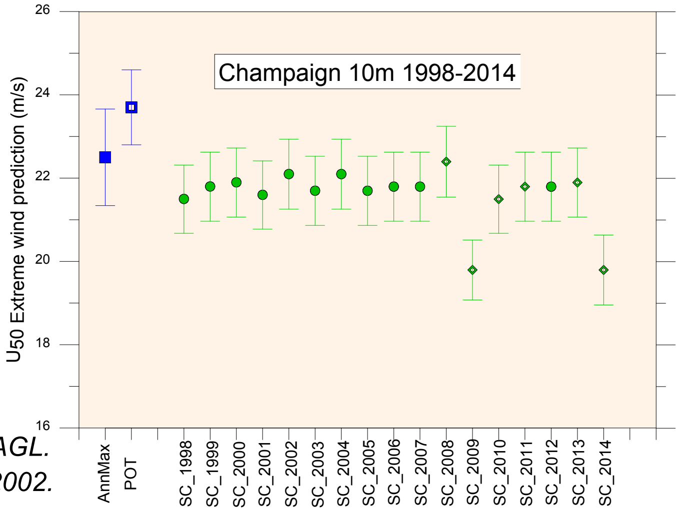


Figure 4.6. Results for Champaign,10 m AGL. Observed spectrum (left) based on year 2002.

Site	**Mast height [m AGL]**	**1-year periods**	**Extreme wind estimations U_{50max} [m/s]**			
			AM method "observed"	**POT method 'observed"**	**Spectral Correction method "predicted"**	
					Average	**Standard deviation**
Horns Rev 1	45	8	N/A	41.4	37.5	0.27
Høvsøre	100	10	42.8	N/A	40.3	0.26
Sprogø	70	22	33.3	34.0	35.2	0.22
Tystofte	39	32	32.1	31.4	32.1	0.14
Cabauw	200	13	39.1	40.1	38.4	0.30
Champaign	10	18	22.5	N/A	21.5	0.80

Table 4.1. Summary of the SC extreme wind calculation (using CFDDA long-term data) compared to 'observed' extreme winds (calculated by the AM and POT methods).

For Horns Rev, the AM-method, depending on only 7 samples, was highly biased by a near-to-100-year storm (see fig.4.1), and thus disregarded in the comparison above. Further, the CFDDA-based SC estimate could be problematic because of uncertain generalization of CFDDA data[4], a problem that was not present for the CFSR-based SC estimate. The POT estimates for Hoevsoere and for Champaign were disregarded because of too uncertain data fitting. For Champaign, two of the SC extreme wind calculations are seen to be “outliers”; with the continental climate of the site this could be due to the presence of repeated downburst families (‘derechos’).

For each of the six sites, it is seen for the SC extreme wind method with CFDDA data that the prediction is within 3.9 m/s lower (Horns Rev 1) and 1.9 m/s higher (Sprogø) than the observed extreme wind speeds, and that the standard deviation of the predicted extreme wind speeds is within 0.80 m/s (Champaign).

5 Conclusion

We have demonstrated and tested extreme wind calculation applying the Spectral Correction (SC) method, which has recently been integrated in a DTU Wind Condition Software. The SC method allows extreme wind calculations to be made from short-term measured wind data series in combination with CFDDA long-term reference wind data, which is available from an internet-database[5].

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 agreement within error bars was found. 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 (Sprogoe) 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 periods of on-site wind data.

The consistency of the SC method has been validated by checking the standard deviations of SC extreme wind predictions. For all six sites the standard deviations 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.

This study has shown that caution should be taken 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. Further the user of the SC-method should always check that the transition of the hybrid spectrum is smooth (from ‘modelled’ to ‘observed’ spectrum). Finally, the SC method should be used 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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[4] For Horns Rev the determination of the roughness length used in the generalization of the applied CFDDA data was uncertain because the CFDDA grid-point was close to a coast-line.

[5] Presently, the data cover Europe, Turkey and the USA. The coverage will be expanded and global coverage is expected in 2017.

Acknowledgments

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