Descripiton of method used for wind estimates in StormGeo

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Introduction

The wind studies made by StormGeo for HybridTech's projects is based on the 1 km WRF model which is set up for the specific areas. This paper contains:

- Description of the WRF model and the model setup, including input data for the model.
- Explanations of methods and assumptions used.
- Corrections to long term climate.
- A discussion about the uncertainty of the production estimate.

The wind data results themselves are delivered in separate files.

HINDCAST – A method for reproduction of local scale climatology

Hindcast means historical weather forecasts with the best possible boundary conditions. By using global scale data in combination with a limited area model it is possible to reproduce the local scale weather in order to better describe the effects on local scale. In this project the main purpose has been to reproduce the wind patterns of the sites and adjacent areas, with high horizontal and vertical resolution. This study has applied the state-of-the-art WRF model which are designed for complex topography and for good description of land surface processes and atmospheric interactions.

The Weather Research and Forecasting model – *WRF*

The Weather Research and Forecasting (WRF- http://www.wrf-model.org/index.php) Model is a next-generation Mesoscale numerical weather prediction system designed to serve both operational forecasting and atmospheric research needs. It features multiple dynamical cores and a software architecture allowing for computational parallelism and system extensibility. WRF is suitable for a broad spectrum of applications across scales ranging from meters to thousands of kilometers. WRF is a widely used atmospheric model globally for research and real-time purposes and has several thousand users (institutions, companies and private persons) worldwide. The main purpose of the WRF community has been to develop the next generation of weather prediction models suitable for resolutions down to a few hundred meters operationally. The need for such systems is increasing and computer technology makes real-time forecasting and long term hindcast studies on resolutions on the 1-10 km scale feasible.

Storm has been running nested, limited area models for real-time weather prediction since early 2003. The in-house forecasting suite has primarily consisted of the Weather Research and Forecasting model, WRF (http://www.wrf-model.org/index.php). WRF has a wide variety of parameterizations of shortwave and long wave radiation, sub-grid scale turbulence, the soil and sea surface, cumulus clouds and cloud microphysics. An important part of model tuning and optimization is to select the best combination of parameterization in order for the WRF setup to have optimum performance. This work is normally done by conducting model sensitivity studies with a variety of model configurations. Based on verifications from these studies, a final Hindcast configuration is set.

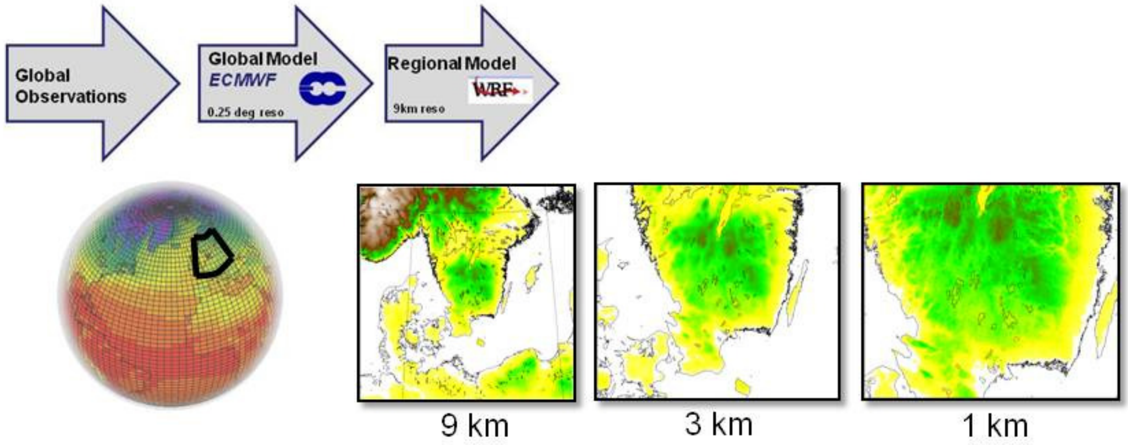

Figure 1: From global to regional scale forecasts. ECMWF is used to provide initial and boundary conditions for the Storm WRF Hindcast.. Shown here are the topography from the WRF domains.

The resolution used for the Hindcast is 1km, nested down from ECWMF to the northern parts of Europe and down to 1km with a vertical resolution of at least 36 layers (see Figure 1) at the focus forecast area. This gives a resolution of the land-sea mask of 1km – enough for a highly detailed description of the coastline and the contrasts between different land surface types. Another important factor is the vertical resolution. Here a setup of 37 layers, with approximately 15 in the lowest kilometre for detailed description of the Planetary Boundary Layer and turbulent fluxes therein are used.

WRF is set up with many sequential model runs based on the ECMWF atmospheric model at 0.25 degree horizontal resolution. The update frequency of the boundary data is 3 hour and is used for lateral boundary conditions for the WRF model domain. For optimum quality many 18 hours forecasts are created in order to maintain high consistency between global scale pressure patterns and local scale wind fields.

ECMWF boundary data has proven to be a very reliable and high quality data source to create forecasts over European domains.

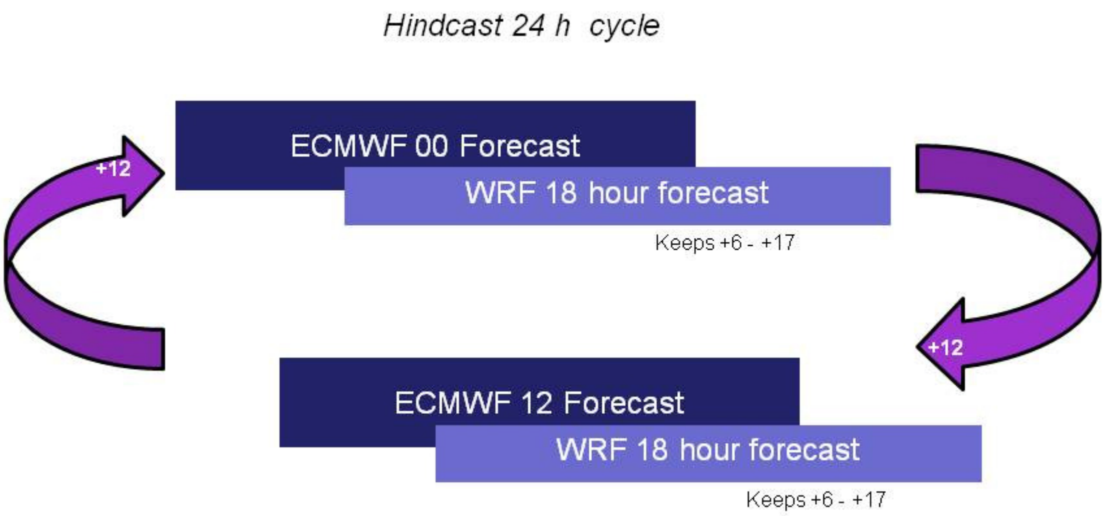

Figure 2: model cycling between WRF and ECMWF. ECMWF is used to initialize the WRF Hindcast cycle every 12 hours.

Global scale data: The European Centre for Medium Range Weather Forecasting – ECMWF

The European Centre for Medium-Range Weather Forecasts (ECMWF, http://www.ecmwf.int/) is an independent international organisation supported by 26 European States. For many years the ECMWF has produced the best global deterministic atmospheric forecasts in the world, see example in figure 3 below.
The principal objective of the ECMWF is to continuously improve global medium range weather forecasting products with a particular emphasis on early warnings of severe weather. The centre uses highly advanced numerical weather prediction (NWP), to forecast the weather from its present measured state. Its complex calculations require a constant input of meteorological data, including air pressure, temperature, wind speed and direction, and humidity. This information is collected by satellites and other observing systems such as automatic and manned stations, aircraft, ships and weather balloons. These observations are assimilated into the forecasting model to produce medium-range forecasts, predicting the weather up to 15 days ahead.
These forecasts are documented to be the best global forecasts in the world, mainly due to advanced assimilation systems (incorporation of observations into its analysis), advanced model dynamics and physics parameterizations and higher horizontal and vertical resolution than its competitors (NCEP – USA and UK Met Office amongst others).

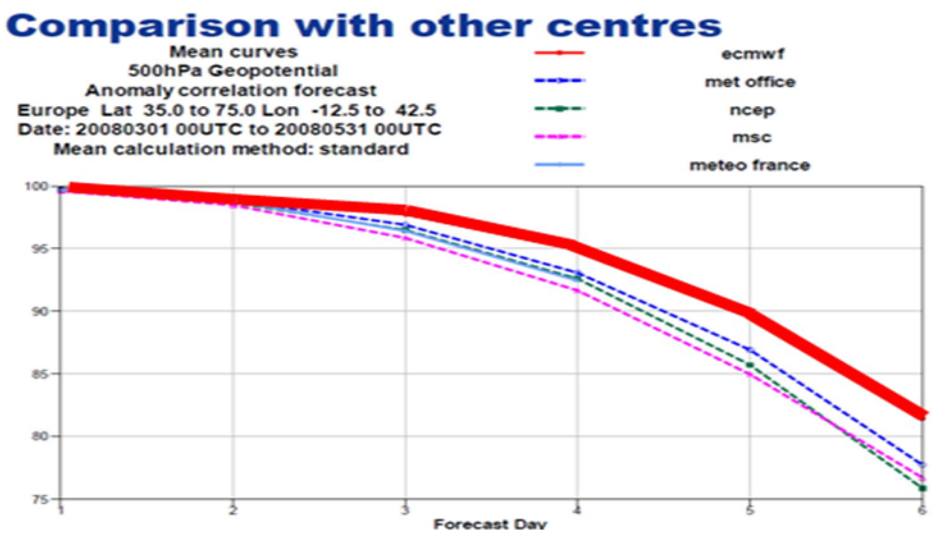

Figure 3: **Comparison of the ECMWF model with other centers running global models.**

Increased computer power combined with a large quantity of satellite data ingested into advanced data-assimilation techniques has lead to a remarkable increase in forecast accuracy during the last 20 years. Improved quality is seen best in areas where traditional observations are sparse including the tropics and over the ocean in the southern hemisphere. A forecast over Europe is today typically reliable for at least a week forward in time compared to 4-5 days in 1980. Details and verification results are shown in http://www.ecmwf.int/publications/newsletters/pdf/106.pdf (page 28-35 and references therein) or at other reports that can be found at http://www.ecmwf.int.

Their model is a coupled modeling system which contains both a wave and an atmospheric model. This means that there is a direct interaction between the atmospheric forcing and the ocean waves and vice versa. An advantage of this coupling is that the roughness from the waves is taken into account in the calculation of wind stress at the surface, giving more accurate and realistic wind speeds over the ocean. The ECMWF model is currently running at a resolution of T799L90, which means that the horizontal resolution is approximately 25 km x 25 km globally
The ECMWF modeling suite has two main updates daily with initial time 00 and 12 UTC. These data are the basis for the updates performed by the forecasters and are also used as boundary conditions for the regional scale model which are setup to serve this Hindcast.

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GEV distribution

Historically, fitting a Weibull distribution has been the traditional way of making estimates of power production. However, there are several weaknesses by doing this procedure. To cite Coles (2001), the weaknesses can be summarized in the following two points:

1) Is Weibull a proper choice? If Weibull is not proper, what should be used instead? A technique is required to choose which distribution is most appropriate for the data.
2) When a choice of a distribution is made, subsequent inferences presume this choice to be correct, and do not allow for the uncertainty such a selection involves even though this uncertainty might be substantial

The choice of using Weibull distribution is logical; its behavior is similar to observed wind distribution. However, there are several ways to optimize the fitting of the distribution to data. The Weibull distribution is a part of a family of extreme value distributions. According to Coles (2001), making an assumption of distribution might result in high bias. An Generalized Extreme Value (GEV) distribution is a generalization of the three distributions Weibull, Gumbel and Fréchet. By fitting a GEV, the fit will potentially be more optimal.

The GEV distribution is defined as follow:

$$F(x;\mu,\sigma,\xi) = \exp\left\{-\left[1+\xi\left(\frac{x-\mu}{\sigma}\right)\right]^{-1/\xi}\right\}$$

where for $1 + \xi(x - \mu) / \sigma > 0$, where μ is the location parameter, $\sigma > 0$ the scale parameter and ξ the shape parameter.

In probability theory and statistics, the generalized extreme value distribution (GEV) is a family of continuous probability distributions developed within extreme value theory to combine the Gumbel, Fréchet and Weibull families also known as type I, II and III extreme value distributions. By the extreme value theorem the GEV distribution is the limit distribution of properly normalized maxima of a sequence of independent and identically distributed random variables. Because of this, the GEV distribution is used as an approximation to model the maxima of long (finite) sequences of random variables.

There are several ways to optimize a distribution to data. At Storm Weather Center AS, L-moments and maximum likelihood method are normally used. However, it is recognized that estimates based on L-moments are generally superior to standard moment-based estimates. The L-moment estimators have some desirable properties for parameter estimation. In particular, they are robust with respect to outliers and their small sample bias tends to be small. L-moment estimators can often be used when the maximum likelihood estimates are unavailable, difficult to compute, or have undesirable properties. They may also be used as starting values for maximum likelihood estimates (Hosking, 1990).

Weibull distribution

The most commonly used distribution used for derscribing the distribution of wind speed is by far the weibull distribution. Though it might not the best (as described in previous section), it is easy to interpret, most people working with wind issues are familiar to it and most of the software developed for wind studies work with weibull distributions for wind.
The classical weibull 2-parameter distribution is defined as

$$f(x;\lambda,k) = \begin{cases} \frac{k}{\lambda}\left(\frac{x}{\lambda}\right)^{k-1} e^{-(x/\lambda)^k} & x \geq 0 \\ 0 & x < 0 \end{cases}$$

The corresponding CDF becomes:

$$1 - e^{-(x/\lambda)^k}$$

The median can then easily be determined by,

$\lambda(\ln(2))^{1/k}$,

and the mean value as:

$\lambda\Gamma\left(1+\frac{1}{k}\right)$, where Γ is the Gamma function evaluated at (1 + 1/k).
Fig. 5 shows an example of the two distributions, GEV 3-parameter and Weibull 2-parameter.

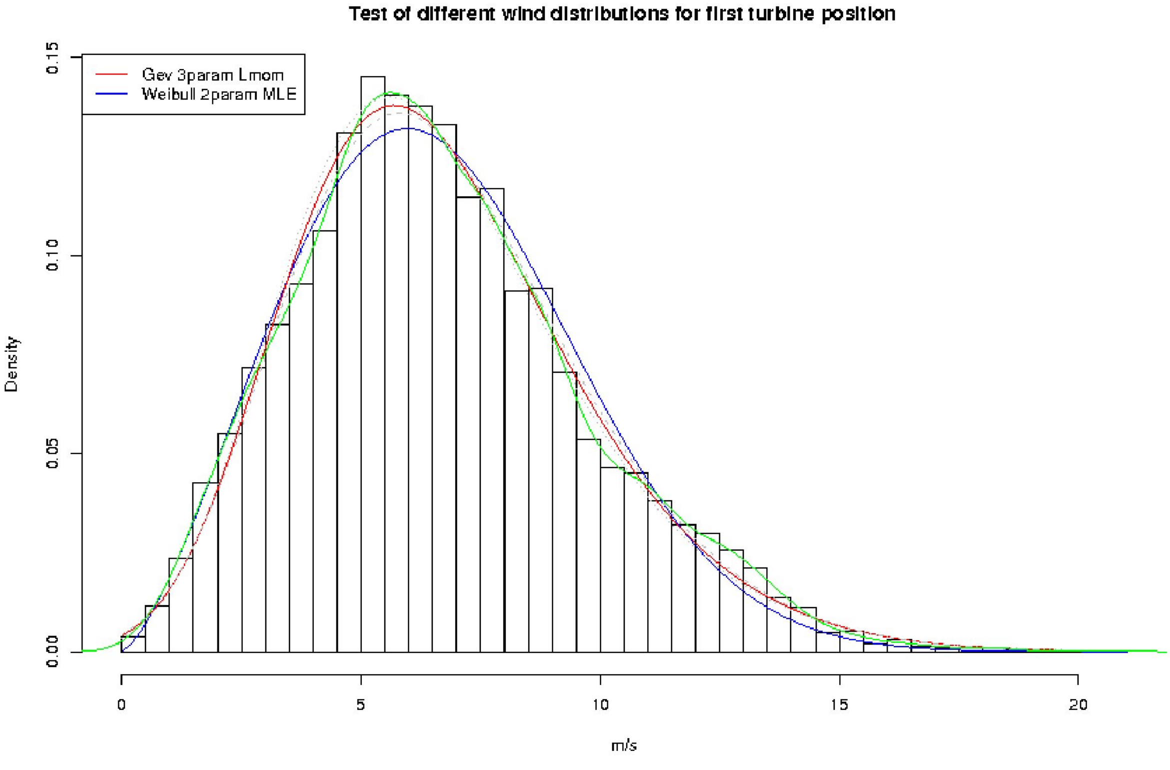

Fig 5. Example of both GEV and Weibull distribution for turbine 1, area 21, 72 m above zero plane.

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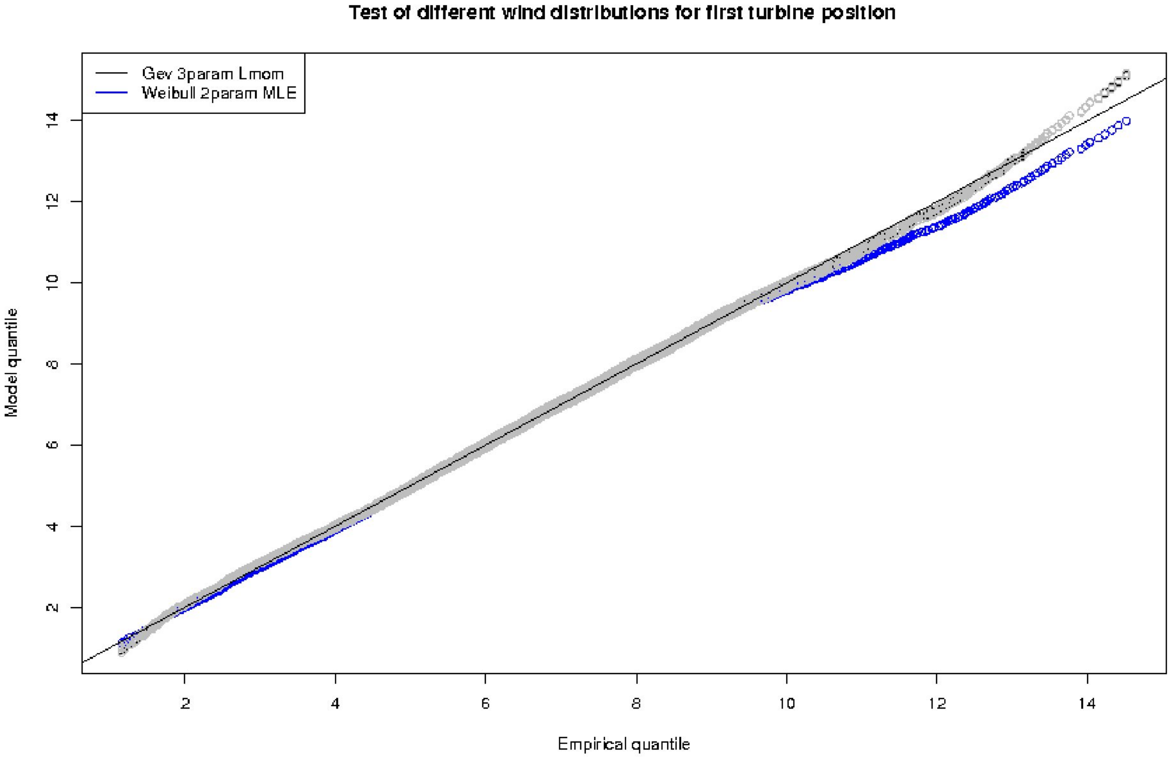

Fig 6. A quantile to quantile plot for the data presented in the above figure. Modelled quantiles against observed. One can see that the GEV distribution is a bit closer to reality than weibull.

Distribution correlation for long term correction

Paul van Lieshout at Sinclair Knight Merz LTD proposes a new method for correlating time series of wind measurments and/or forecasts. This method is based on a weibull feedback correlation method presented at EWEC 2009 in Marseille. One common approach is to find the correlation through numrical analysis, using a straight line approach or polynomial functions. The weibull feedback method is a more analytical method, using a mathematical function that describes the characterstics of the wind speed.

The weibull feedback methology is based on making a tranfser function between the to timeseries, letting the CDF for the short timeserie wind speed as a function of the long timeserie wind speed equal the CDF of the long time serie wind speed like:

$cdf(v_s[v_m]) = cdf(v_m)$

Using the following parameters,

- v_s – wind speed on site (short serie)
- v_m – wind speed on nearby met station (long serie)
- λ_s - weibull lamda for site
- λ_m - weibull lamda for met station
- k_m - weibull k for site
- k_s - weibull k for met station

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and the Weibull CDF function from the previous section gives us v_s as a function of weibull parameters and v_m:

$$v_s[v_m] = \lambda_s \cdot \left(\frac{v_m}{\lambda_m}\right)^{k_m/k_s}$$

Then use v_m , the whole time serie, to calculate the correspondning time serie for v_s . Now we have a new wind speed average and weibull distribution for the site of interest corresponding to the whole period of measurment data form the met observations site.
Storm Weather Center has developed this method further by also using a GEV distribution instead of a weibull distribution. Using the following parameters,

- v_s – wind speed on site (short serie)
- v_m – wind speed on nearby met station (long serie)
- ξ_s – GEV shape parameter for site
- ξ_m – GEV shape parameter for met station
- σ_s – GEV scale parameter for site
- σ_m – GEV scale parameter for met station
- μ_s – GEV location parameter for site
- μ_m – GEV location parameter for met station

and the GEV CDF function presented in the GEV distribution section gives us v_s as a function of GEV parameters and v_m:

$$v_s[v_m] = \mu_s + \frac{\sigma_s}{\xi_s} \cdot \left[\left(1 + \xi_m \cdot \left(\frac{v_m - \mu_m}{\sigma_m}\right)\right)^{\xi_s/\xi_m} - 1\right]$$

Long term correction

Both the weibull correlation method and the GEV correlation methods are used for correcting the result to 'climate mean' result. Often they give about the same result, but occasionally they can differ by a few percent. The difference appears when the distribition differ from a perfect weibull distribution.
For the annual energy production (hereafter AEP) estimates, P50, P75, P90 and P99 the result from the GEV distribution is used.
This method is also used to find the year by year AEP for the last 20 years.
Correlations and corrections are applied to both the observations and the forecast data for each turbine. The long term data comes from the ERA INTERIM reanalysis data set from ECMWF (European Center for Medium Range Weather Forecasts) in Reading, England. At Storm Weather Center we have data at a resolution of ~0.7 degrees, and data is bilinearly interpolated to each turbine position. The data consists of temperature and wind data for each 3rd hour for 20 years from 1989 to 2008. For the correlation we're using data from the 4th and 5th model level from the ground, that is between 80 and 140 m above model surface. For more information on ERA INTERIM please look at http://www.ecmwf.int/research/era/do/get/era-interim .

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Several comparisments have been made at other sites between using ERA data and using nearby SYNOP station as the long term climate data. The correlation with nearby SYNOP stations has often been between 0.5 and 0.8. For ERA INTERIM, it has been closer to 0.9.

Errors and uncertaintes

Please note that the Hindcast method does not include a detailed study of microscale turbulence, small-scale wind shear and inflow angle effects.

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