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PREDICTING THE WIND ENERGY RESOURCE IN THE OFFSHORE SEAS OF EUROPE

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1. INTRODUCTION

Replacement of fossil fuel-based energy generation by renewable technologies offers the potential to reduce greenhouse gas emissions. In most European countries, wind energy is the renewable resource that has undergone the greatest expansion in the last twenty years. However, there are public concerns about visual intrusion and noise, which means that it can be difficult and slow to obtain planning permission for wind farm development on land. Against this background, offshore wind farm development appears increasingly attractive, despite higher construction and maintenance costs. Offshore wind speeds should be at least as high as at many onshore sites, and public concerns should be fewer.

When planning a wind farm onshore, a developer will typically measure wind speeds for a period of at least one year, in order to evaluate the available resource. Offshore, this may be prohibitively expensive. This paper reports results from the three-year multi-institution POWER research project, ‘Predicting the Offshore Wind Energy Resource’, which set out to evaluate the size and characteristics of the wind energy resource for the offshore waters of European nations (Halliday et al., 2001). The goal was to produce useful information for developers on the characteristics of the offshore wind field.

POWER is based on a two-step modelling procedure. The first step is to model the wind field over the open sea, away from coastal effects in the land/sea transition zone. The second step is to apply a coastal discontinuity model (or CDM) to predict the wind field taking account of atmospheric stability effects. This is done by:

i. calculating the geostrophic wind speed and direction from gridded sea level pressure data; then,
ii. transforming the geostrophic wind to the sea surface layer by applying the Wind Atlas Analysis and Application Program (WA^SP, see Mortensen et al., 1993).

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Research in support of these modelling activities has included:

- Construction of confidence limits on the model predicted estimates of wind speed.
- Validation of model estimates using observed data from offshore masts, coastal anemometer sites and radiosonde ascents.
- Exploration of time-dependent variability in the wind field, on time scales from decadal to diurnal.
- Installation of SODAR instruments in the far offshore and coastal zones to explore the vertical structure of the wind field.

A flow diagram of the methodology is shown in Fig. 1.

2. FAR OFFSHORE WIND SPEEDS

The POWER analyses were applied over the region 30-70°N by 15°W to 30°E, which covers the Baltic and Mediterranean Seas as well as the NE Atlantic (see Fig. 2).

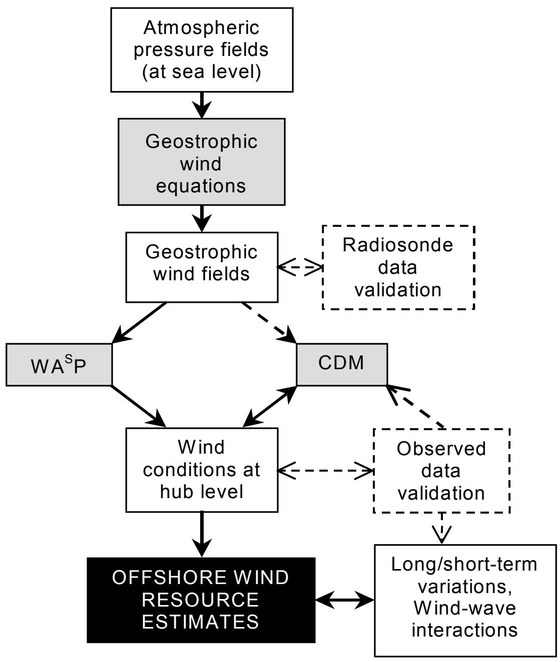

Figure 1 Flow diagram of the power methodology

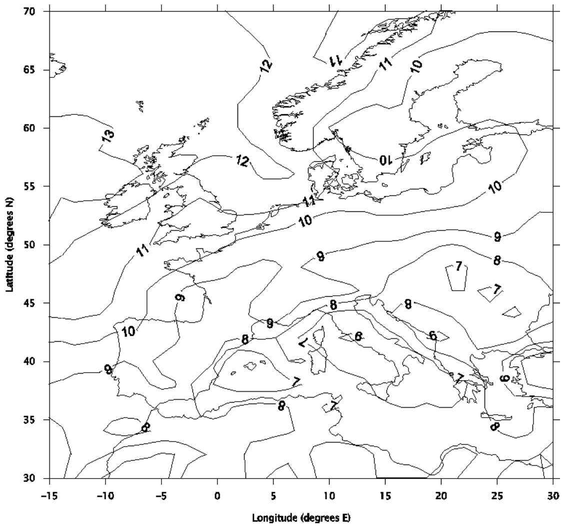

Figure 2 Calculated mean annual geostrophic wind speeds (m s^{-1}) – 1985 to 1997

2.1 The Geostrophic Wind Field

Geostrophic wind speeds and directions were calculated from six-hourly gridded (at a resolution of 2.5^o latitude by 2.5^o longitude) mean sea level pressure data from the National Centers for Environmental Prediction (NCEP). Data covering the period 1985 to 1997 were interpolated onto a 0.5^o latitude by 0.5^o longitude grid using bicubic spline interpolation. The pressure gradient at each grid point was then used to calculate the geostrophic wind speed and direction for each grid point and time step. The mean annual geostrophic wind speed is shown in Fig. 2.

Validation of the geostrophic wind speeds was performed using radiosonde data. Thirty-seven records from low-lying coastal stations were obtained from the British Atmospheric Data Centre. These fulfilled the criteria that a continuous record of twice-daily ascents should be available from 1990 to present. For a proper comparison with geostrophic wind speeds, radiosonde data were required from above the friction layer – therefore, data sets were extracted of the first occurrence of a measurement at a height between 600 and 900 m. Fig. 3 compares the seasonal cycle of geostrophic and radiosonde wind speeds for the Baltic (based on eight stations) in the overlap period, and shows close agreement.

2.2 Translation to the Near-surface

The linear flow model WA^{S}P was used to transform the calculated geostrophic winds to the surface layer, at each point in the 0.5^o by 0.5^o grid over the sea. This required WA^{S}P analyses to be performed at over 3700 locations. Average annual and monthly wind conditions were estimated at eight potential wind turbine hub heights (10m, 30m, 50m, 70m, 90m, 110m, 130m and 150m above sea level). A simple representation of coastal effects was employed. Where a grid point is situated far offshore (>10km), a constant roughness value of 0.0001m was assumed. Where a grid point is close to the coast (<10km) a roughness value of 0.0001m was assumed over the sea and 0.03m over the land. Example results for 50 m above sea level are shown in Fig. 4. WA^{S}P was also used to estimate the mean annual offshore wind energy resource.

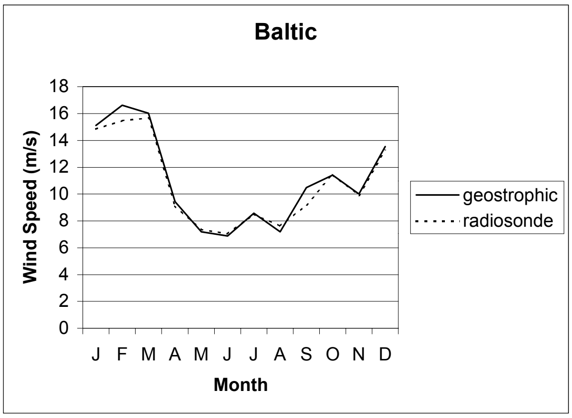

Figure 3 Seasonal cycle of geostrophic and friction-free wind speeds

2.3 Confidence Limits

A simple estimate of the mean wind speed is insufficient without some indication of the associated uncertainties. Confidence limits were calculated by bootstrapping for the WA^{S}P predictions of hub-height wind speeds. These predictions are for each month, presented as the Weibull shape (*k*) and scale (*A*) parameters for each of 12 directional bins, together with the percentage frequency of winds in each bin.

The formula to create a random number *x* from a Weibull distribution is:

$$x = A\,(-\log(1-p))^{1/k} \qquad \ldots 1$$

where *p* is a probability generated by a uniform random number routine. A 100-value time series of wind speed was generated for each directional bin from (1). Then, this time series was resampled with replacement 1000 times and confidence limits estimated using the bias-corrected percentile method described by Davison and Hinkley (1997). To arrive at an overall mean wind speed for a particular month at a particular gridpoint, the bin means are weighted according to the percentage frequency of winds in each bin, and summed. The 95% confidence limits for the overall mean are derived by applying the same frequency weighting procedure to the confidence limits for each directional bin. Using bootstrapping was found to be much more computationally efficient that using Monte Carlo simulation.

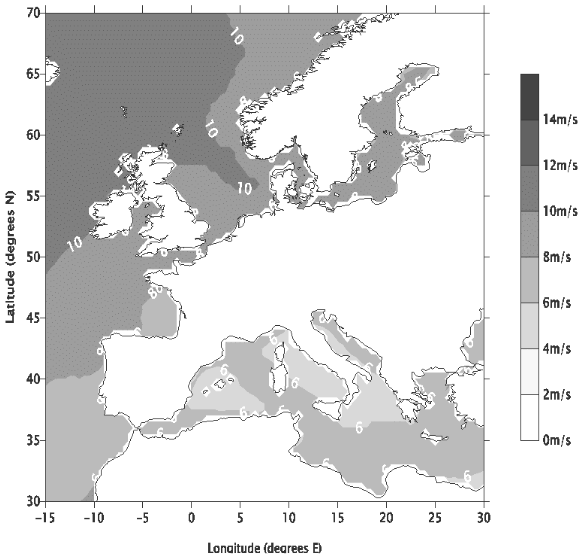

Figure 4 Mean annual wind speeds in the offshore seas estimated by WA^{S}P

3. MODELLING THE COASTAL DISCONTINUITY

The use of WA^{S}P wind speed predictions as input to the CDM has been investigated. The CDM is a combined stability and internal boundary layer (IBL) model developed at Risø. It is based on similar principles to WA^{S}P, the major difference being that on- and off-shore stabilities are calculated at each time step, whilst WA^{S}P uses mean offshore and onshore corrections. The former approach has been shown to improve offshore wind speed profile predictions in some cases. The stability corrections are then used to modify offshore wind speed profiles from the logarithmic while accounting for the differential growth of the IBL in varying stability conditions.

The CDM was reconfigured to accept WA^{S}P-predicted wind speed distributions for each sector and then to determine the stability correction from time series of air and sea temperatures taken from the NCEP reanalyses. Unfortunately the only method currently available is to calculate mean stability corrections for each sector, which did not improve the average wind speed profile predictions. The reason for this is that individual time series corrections of wind speed profiles for stability can either be positive or negative - hence calculating the average of the corrected wind speed profiles does not give the same result as calculating an average of the stability corrections and then using this to correct the mean wind speed profile. However, the method shows promising results and evaluation is underway for coastal regions where stability regimes deviate significantly from conditions which are near-neutral on an annual average basis (Barthelmie, 1999).

4. TIME-DEPENDENT VARIABILITY

Time-dependent variability was explored over a range of scales. Two examples are given here, of very long (century scale) variability, and of short-term (diurnal) variability.

4.1 Long-term Variability

The UK Met. Office provides a Northern Hemisphere mean sea level pressure data set gridded at 10^{o} longitude by 5^{o} latitude and available from 1900 to present as daily data with few missing values. These were used to calculate geostrophic wind speeds at the daily scale, which were then used to calculate monthly values.

In order to understand trends and patterns in the data set of monthly geostrophic wind speeds, a principal components analysis (PCA) was performed with varimax rotation. There were 54 grid nodes in the initial data set, and these were reduced by the PCA to just seven significant factors explaining 83.6% of the variance. The spatial pattern of Factor 1, which affects mainly the Baltic Sea, is shown in Fig. 5. Wind speeds from grid squares strongly related to Factor 1 (i.e. from the Baltic Sea, North Sea and Southern Scandinavia) have been averaged and are plotted in Fig. 6. These display a long-term rising trend.

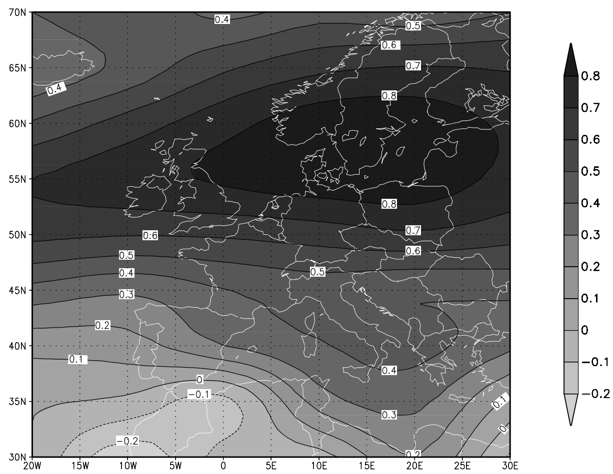

Figure 5 Factor 1, explaining 26.4% of the variance

4.2 Diurnal Variability

The diurnal cycle in wind speeds was explored using two data sources:

- Hourly wind speed data from standard anemometers (10m above the ground) in coastal locations were obtained from BADC. From maps, the compass directions for land and sea fetches were determined. The wind speeds were then sorted into land and sea fetches, and the diurnal cycles plotted by season. The results show:
    - o A strong diurnal cycle in wind speeds with a land fetch, which is particularly marked in

summer, but weak in winter. The amplitude of the cycle is greater than the amplitude of the seasonal cycle. For example, spring winds at night are on average lower than winter wind speeds, whereas the reverse is true from around 0800 to 1800 GMT.
  - An almost total absence of a diurnal cycle in winds with a sea fetch. Where diurnal variations are present, they tend to reach a minimum in the afternoon, and peak at night.
- Mini-SODARs were located at a far offshore site (a gas platform in the North Sea) and a coastal location (on the North Norfolk coast in the UK). The coastal instrument operated for two summer months. Fig. 7 shows how the diurnal cycle varies with height for winds with a land and sea fetch. (Sea fetch winds are only shown up to 100m; above that height there were too few observations to draw meaningful conclusions.) Note how, in the sea-fetch winds, there is little evidence of a diurnal cycle at 10m, but that at height there is a marked reduction in winds speeds at around midday.

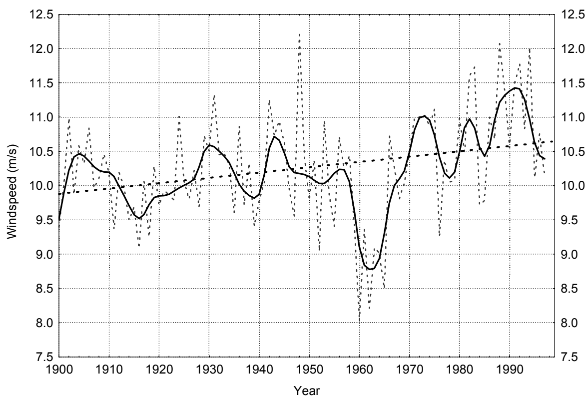

Figure 6 Winter (Oct. – Feb.) wind speeds associated with Factor 1

5. CONCLUSIONS

The POWER project is currently reaching its conclusion, and efforts are being devoted towards dissemination of the results to the wind energy community. The combination of a model-based approach to the prediction of offshore wind speeds, augmented by analyses of observational data to improve understanding of the wind regime, should generate useful results for developers involved in decision making for wind turbine location in the offshore zone.

ACKNOWLEDGEMENTS

The work was partially supported by the European Commission, under DGXII Non-Nuclear

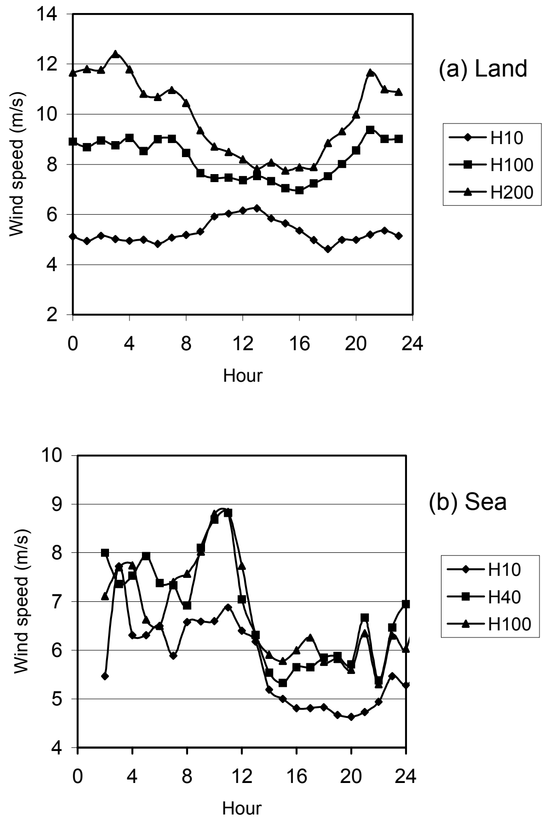

Figure 7 Wind speed diurnal cycles at a range of heights (in metres)

Energy Programme, contract JOR3-CT98-0286 – POWER (Predicting Offshore Wind Energy Resources). The Project Co-ordinator is Dr J.A. Halliday of the Rutherford Appleton Laboratory.

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