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Offshore wind resource assessment in European Seas, state-of- the –art. A survey within the FP6 "POW'WOW" Coordination Action Project.

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ABSTRACT

To plan an offshore wind farm, a careful analysis of wind climatology and profiles of wind and turbulence is needed up to at least 100 m above the sea within about 50 km from the coast. However, installation of offshore high masts is very expensive. Therefore, to supply information in absence of long-term mast measurements, research addresses issues such as the reliability of remote sensing from satellite, methodologies based on onshore measurements in nearby coastal areas or numerical modeling at different time/space scales. These issues have been investigated in different national and European projects especially in North Europe. In other European seas, such as the Mediterranean Sea, there is a lack of offshore measuring campaigns finalized to wind energy applications and evaluation of alternative methodologies have been performed with sparse data mainly from buoys. The main differences between coastal area wind climatology in North and South European Seas is associated to stability conditions, sea breeze regimes and local winds, frequency of calms, and complexity of topography of the coastline. One of the purposes of the Wind Resources Assessment work package in the POW'WOW project is to review the state-of-the-art in the field. This paper contains a review of relevant methodologies to estimate regional offshore wind climatology in European Seas and examines experimental efforts expected to provide data for both testing parameterizations of the underlying physical processes and assessing the accuracy of model predictions.

1. INTRODUCTION

The EEC "European Wind Atlas" project, which ended in 1988, led to the development of the "Wind Atlas and Application Program"(WAsP) [Troen and Petersen, 1989] for the simulation of regional and local surface wind statistics on the basis of conventional weather observations, and orographic and topographic information. WAsP is a fast and user friendly tool and it has been the standard tool to estimates regional wind climates to assess surface wind climate within the areas with same regional wind conditions since it came out. However, to define the extension of regional climate areas is a crucial issue and it presents limitations in offshore coastal areas since WAsP does not specifically model thermal wind such as the sea breeze; furthermore, the lack of specific stability climates tend to force adjustment in the coastal zone to the first 5-10 km after which the wind speed reaches an equilibrium.

Since 1999, large wind farms with wind turbines up to 5 MW have been erected offshore especially in the North Sea, i.e. Denmark and Scotland. Offshore wind speeds tend to be higher than those over adjacent land areas (except where orographic forcing is present) due to lower roughness, which also results in lower ambient turbulence offshore. If offshore atmospheric stability conditions deviate significantly from near-neutral (either on average or by season) the effect of missing stability correction in the wind speed profile can be substantial. Relatively few studies have been performed on the evaluation of offshore wind resources and these are mainly concentrated in North Europe. Various methodologies including satellite and ground base remote sensing and model techniques are available for predicting long-term wind speeds in offshore areas. In this paper, we present a survey of the available datasets and the state-of-the-art work and relevant results from their application.

2. DATA

Basically, we consider as data, any output from direct or indirect measurement technique i.e. in-situ, or using remote sensing both ground (Lidar and Sodar) and satellite based. For wind farm siting the optimal solution is to have a long time series of measured data at the site of interest, and information about vertical wind profiles. Offshore, this information is frequently missing, therefore, a long term measuring programme is desirable although expensive, both in

financial and time terms. In this section, we give an overview of the completed or existing measuring programmes and of efforts to exploit remote sensing techniques.

Offshore wind resource estimation has a number of special issues. The thermal stability of the atmosphere has an important effect on the vertical wind profile and on estimates of the wind resource at a particular height; therefore, a correction to the logarithmic profile must be applied to take it into account and even this simple model may not account for the complexity e.g. [*Gryning, et al.*, 2007], [*Tambke, et al.*, 2005]. Onshore, thermal stability has a daily cycle and in windy cloudy days the assumption of neutral atmosphere neutrality is often a good one. Offshore, atmospheric stability depends on the temperature difference between sea and air. To attribute the correct roughness to the sea surface is also a problem; roughness depends on the sea state which is also a function of the depth of the sea: this is a problem in coastal areas where the depths decrease with the distance to the coast. However, it has been shown that varying sea surface roughness has a minor impact on wind speed profiles [*Barthelmie*, 2001a], [*Lange et al.*, 2004].

For offshore winds the air flow encounters a rough to smooth transition and the internal boundary layer development in such a case is still under discussion see e.g. [*Sempreviva, et al.*, 1990].

2.1 In-situ offshore measurements

Prior to 1990, wind speeds were seldom measured offshore for wind energy but rather measurements were made for meteorological services [*Bumke and Hasse*, 1989]; [*Schmidt and Puttker*, 1991] on ships [*Graham*, 1982; *Quayle*, 1980] or on oil and gas platforms. Although these have been used to assess wind resources [*Coelingh, et al.*, 1996; *Matthies, et al.*, 1995] they are typically of insufficient accuracy for the prediction of wind energy from specific sites.

Also, specific measurements for offshore wind farms have been mostly undertaken below 100 m in height. Here, assuming that the constant flux layer assumption holds, wind speed profiles are generally more accurately predicted using atmospheric stability corrections based on Monin-Obukhov similarity theory than using the logarithmic profile [*Motta, et al.*, 2005; *Van Wijk, et al.*, 1989]. However, recent evidences from wind speed profiles measured above 50 m suggest that the use of similarity theory may not be adequate for offshore wind speed profiles above 50 m [*Tambke, et al.*, 2005]. Measurements programmes have been made at prospective offshore wind farm sites using purpose built meteorological masts at a number of sites in northern Europe. These include those in Denmark [*Barthelmie, et al.*, 2005], Germany [*Neumann, et al.*, 2004], Sweden [*Ganader, et al.*, 2001] and the UK although the latter are not well described in the literature due to commercial confidentiality. One of the main issues of extrapolating vertical wind speed and turbulence profiles to turbine hub-heights without the use of a tall meteorological mast has been addressed using both sodar [*Coelingh, et al.*, 2003], [*Barthelmie, et al.*, 2003] and more recently lidar [*Antoniou, et al.*, 2006].

2.2 Satellite mapping

During the last 10 years, the use of satellite spatial and temporal information has been shown to be a valid support for wind energy assessment especially as an instrument to validate modelling efforts. Satellite data have a number of issues [*Barthelmie and Pryor*, 2003], [*Pryor, et al.*, 2004] although there are clear advantages in terms of the spatial coverage of information [*Hasager, et al.*, 2004]. The two main used observation products are SAR (Synthetic Aperture Radar) and scatterometer images. SAR such as the instruments installed onboard European Space Agency (ESA) ERS-1&2 can provide reliable wind maps cover of the coastal zone starting from 3 km offshore with very detailed information. Typical grid resolution for wind energy mapping is of 400 m by 400 m as a compromise between noise reduction and high image resolution. Satellite scatterometer wind observations from SeaWind instrument on board of the NASA satellite Quik-SCAT have a spatial resolution of 25 km x 25 km. These data are not relevant as close to land as SAR due to the coarser resolution respect to SAR images. [*Monaldo, et al.*, 2004] found a mean difference of 0.35 m/s in a SAR to scatterometer wind speed comparison in the Gulf of Alaska. Both types of sensors provide statistics that could be used in models to assess the coastal wind power potential. Sensors such as SAR and scatterometer have the clear advantage that they penetrate clouds and are not dependent on sun illumination of the remotely sensed objects. A disadvantage in the use of SAR is that only are obtained 3 to 8 times monthly whereas scatterometer wind data are more frequent being available ~ twice per day. The relatively low number of samples and the absolute uncertainty within the maps, (~ 1.3 ms^{-1}) [*Goodberlet, et al.*, 1989] offer wind resource statistics useful only in pre-feasibility studies or in combination with classical offshore observations and modeling.

Another issue is that a *a-priori* estimate of the wind direction must be provided by methods based on 2-D FFT or wavelet analysis with a 180º ambiguity, which must be resolved by the user.

2.2.1 Wind Maps from SAR

Various studies on wind resources assessment using SAR data where carried out in various project funded by National or international Agencies i.e. the European Commission or European Space Agency.

In the EU FP5 "WEMSAR" Project, wind speed maps for various atmospheric situations were retrieved at several European test sites, i.e. the west coast of Norway, the Horns Rev off-shore site in Denmark, and the Maddalena Island in the northern part of the Sardinia Island in Italy and compared to offshore wind resources from local scale (WAsP) and a regional scale (KAMM) models. The purpose of this project was to provide a tool for offshore wind resource assessment [*Hasager, et al.*, 2005]. The WEMSAR tool consists of two modules: a SAR wind retrieval module and a statistical *Module 1* was developed for wind retrieval from ERS SAR images [*Furevik and Espedal*, 2002]. In the

second *Module 2*, the output files from the wind mapping module are read into the statistical module where all satellite wind fields are treated together to provide wind climate input to the WAsP micro-siting model.

Results of WEMSAR in North Europe

A comparison of wind speeds derived from SAR, Quik-Scat and in situ data at the Horns Rev wind farm illustrated that SAR-derived wind speeds tended to be lower than in-situ observations [*Hasager, et al.*, 2006].

Results of WEMSAR in the Mediterranean Sea

The station was a 10m offshore tower situated in the narrow strait between Sardinia main-land and the Maddalena Island. Wind measurements were available as 10-min mean speeds for the period January 1997 – June 1999. Wind directions from SAR were in fairly good agreement with in situ measurements whereas the SAR wind speed values differ somewhat from in situ measurements. This can be explained by the location of the tower in between islands.

2.2.2 QuikSCAT

QuikSCAT currently provides the most frequent global coverage with observations twice per day for most of the globe (missing a little near the equator). See e.g. *http://earthobservatory.nasa.gov/Library/QuikSCAT/*

North European Seas

Comparison of QuikSCAT derived winds with observations at Horns Rev indicated a relatively high correlation coefficient of 0.91 between the two datasets [*Hasager, et al.*, 2006].

Mediterranean area

An evaluation of the added value of satellite data for providing spatial information and validating models and methodologies for offshore wind climatology over the whole Mediterranean basin was presented in two papers. The wind climatology over the whole Mediterranean basin using the six years of wind data by QuikSCAT, in terms of spatial variation of wind roses, mean wind speed, seasonal and monthly variation was presented in [*Sempreviva, et al.*, 2006] and compared to wind data from three models (see next sections) i.e. the analyses from the European Centre for Medium-range Weather Forecasts (ECMWF), the GeoWAsP model, and the Climate Model LMDZ. The Level 2B swath data (July 1999 – August 2005) were downloaded from the PODAAC server at http://podaac.jpl.nasa.gov/products/_product108.html and gridded into a 0.25º x 0.25º grid for the Mediterranean. The coordinate pairs of the low left corner and right upper corner of the area are (–7.5º E, 30º N) and (36º E, 47º N) respectively. For each grid point, mean wind speed U (ms^{-1}), scale parameter A (ms^{-1}), and shape parameter k of the Weibull frequency distribution function have been calculated for 12 directions of 30 degrees each. Only QuikSCAT data classified as "best data" have been used in this study. Therefore only QuikSCAT wind speeds between 3 ms^{-1} and 20 ms^{-1} are included. Due to the relatively coarse resolution of 25 km x 25 km, in a zone with several islands like the Aegean Sea, QuikSCAT data are less reliable than in open sea. Maps of annual and seasonal mean wind speed have been produced. To evaluate the relative performance of models, grid points located in different areas of the Mediterranean basin were selected and frequency distributions, seasonal and monthly features were compared. In this case, QuikSCAT gives higher values of mean wind speed U since only wind speeds u larger than 2 ms^{-1} were considered reliable and retrieved in the time series, resulting in a bias in the mean value U. However, there is generally fair agreement on the monthly and seasonal variation at all sites and, as expected, all models agree best far from the coast. Offshore data from islands, platforms and buoys have been used to validate satellite data and models in terms of seasonal and monthly variation. Further work is in progress including all wind speeds below 2 m s^{-1} and comparing to the LMDZ model run at comparable resolution. In the same paper, QuikSCAT climatology was also compared to wind climatology from three experimental offshore sites around Italy (two islands, a platform and a buoy) and to five Greek buoys. Again, there is good agreement in open sea but differences remain in enclosed seas or with high density of islands, where thermal and local wind influences and low resolution of the models and satellite are important factors.

3. METHODOLOGIES FOR BUILDING OFFSHORE CLIMATOLOGY FROM NON IN-SITU OFFSHORE DATASETS

3.1 Statistical methodologies using coastal stations

These methodologies rely on long-term measurements at nearby land sites in comparison with short-term records offshore. In particular, three methodologies have been used in the evaluation of wind resources at Danish offshore sites and have shown to give promising results there [*Barthelmie*, 2001b]. Following we present an overview of the different methods used to estimate the wind climatology offshore.

1) The standard measure-correlate-predict (MCP) method. E.g. [*Bunn and Watson*, 1996; *Rogers, et al.*, 2005]. It assumes a linear relationship between wind speed at paired sites where one site with a long-term record acts as predictor and the wind speed at short-term measurement sites as the predictand. Once a regression equation has been conditioned based on the measurement overlap period, the regression parameters can then be used to derive an extended data record for the site of interest. This method is generally applied using one regression analysis for each wind sector.

2) Risø's Wind Atlas Application and Analysis program WAsP®. [*Mortensen, et al.*, 2005]. It calculates the wind climatology at one site from the wind climatology of long term representative stations. WAsP is a physically-based model and uses a standard heat flux on- and off-shore to calculate a mean stability correction and the change in roughness to adjust the momentum flux.

3) The Weibull correction method [*Højstrup*, 1998] for extrapolating wind data series is based on the concept of modifying the Weibull parameters of the short-term data series to characterise a longer data sampling period. It compares sector-based wind speed distributions at the on- and the off-shore sites considering the on-shore long-term time series as representative of the area. The Weibull shape (A) and scale (k) factors are determined for 12 sectors at both sites considering a common period and their ratio is used to modify the long-term wind speed direction distribution to represent the off-shore station.

At the Danish sites, MCP tends to under-predict wind speeds in comparison with offshore data, which appears to be the result of a shift in the wind speed distribution between on - and offshore. WAsP® typically gives good results except at sites that are less than five kilometres from the coast where wind speeds are predicted to be a few percent higher than those observed. The Weibull method gives good results provided sufficient data are available to accurately characterise the wind speed distribution in each sector and the distribution conforms to a Weibull distribution.

3.1.1. Results in North Europe

A number of studies have been conducted to produce wind resource maps for specific areas. These include the North and Norwegian Seas [Børreson, 1987] and [Korevaar, 1990]. For the Baltic a comparison between WAsP and a meso-scale model [Bergström and Barthelmie, 2002] showed good agreement for prediction of 50 m wind speeds away from the coast (±3%) but larger differences (10-20%) in coastal areas which has been ascribed to stability variations which are not accounted for in WAsP. A larger study using a combination of WAsP with geostrophic wind speeds [Watson, et al., 2000] produced a map of wind speeds between 10 and 130 m height for all European waters which was in good agreement with a WAsP study using data from land based stations to predict offshore wind speeds [Petersen, 1992].

A current study in the North Sea using the FINO-1 offshore platform wind data [*Neumann, et al.*, 2004] from heights of 30m-100m extrapolated to 10m and selected island station data at 10m has shown a moderate correlation of 0.68-0.81 for the overlapping 3 year period [29] [Sood et. al., 2007]. The relatively high correlations coefficient of 0.81 occurs due to the free flow from the dominant wind sector towards south and west. Most recent resource assessment studies in the North Sea use the FINO-1 measurement using WAsP method and modified for the local site conditions using correlations to selected station data and regional wind indices combining methods 1), 2) with mesoscale modelling.

For the North Sea, in a recent study the WAsP method and the mesoscale model MM5 have been compared [Jimenez et al., 2007]. WAsP was used to assess the annual mean wind speed for 2004 over the German North Sea region with data from one onshore, two offshore and three island measurements. The results largely depend on the measurement station used as reference. Four of the six stations investigated, three island sites and the FINO platform, predicted the mean wind speed of each other with good accuracy within ±2%, despite their large geographical distance. The study also compares the vertical wind speed profile calculated by WAsP with the one measured at FINO. A good agreement was found with only a slight underprediction of the increase of wind speed with height. Also interesting for the North Sea, is the influence of tides on the wind speed. Tidal currents lead to a changing surface for the wind profile above it. Water level variations change the height above sea level for fixed structures which therefore effectively move up and down through the wind shear profile. In the intertidal zones, i.e. areas which are covered by water at high tide, but fall dry at low tide, the roughness changes with the tide influencing the wind. The Wadden Sea is a large intertidal zone at the German North Sea coast, which influences the wind regime at the coast, the islands and the offshore areas near the coast. A recent study [Jimenez et al., 2006] compared WAsP calculations for times with high and with low tide for a number of stations close to the Wadden Sea. The largest differences appeared when island stations were used as input or predicted by other sites, whereas predictions based on onshore and offshore stations are practically similar. Also, the stations located in the eastern part of the North Sea exhibit the largest differences between high and low tide predictions. In this area the intertidal zone is broader, reaching up to 10 km.

For the Baltic Sea, a comparison of WAsP calculations with the data of offshore masts at Danish wind farm locations has been performed [Lange and Højstrup, 2001]. Measurements of a coastal and an inland station were used for the predictions of the offshore sites. It was found that the predictions of the long-term average wind resource are in good agreement with the measurements. The only deviation found was for two sites, where the measurements show a difference in the wind resources, which is not predicted by WAsP. Deviations in the directional wind speed predictions were found to correspond with the length of the sea fetch: For smaller sea fetches WAsP seemed to slightly over-predict the wind speed, while for long fetches of more than 30 km an under-prediction was found.

The influence of thermal stability and sea surface roughness on the wind profile were investigated at the Danish measurement site Rødsand in the Baltic Sea [Lange et al., 2004] and the German measurement site FINO 1 in the North Sea [Lange, 2005]. The vertical wind profile of the WAsP model has been compared with that described by Monin-Obukhov theory. The profiles were found to agree well with the FINO I data, but not with the Rødsand measurement. The authors believe that the reason for this is the flow modification at the coastline leading to a mixed layer flow with capping inversion, which can not be captured by Monin-Obukhov theory. This changes the flow at the Rødsand site, where distances to land (fetch) are between 10km and 100km. At the FINO 1 site, where the fetch is generally much larger, similar effects were not found in the present data set. In comparison to Monin-Obukhov theory the WAsP method showed smaller deviations. This shows that the very simple assumption of a mean atmospheric stability in this case performed even better than the use of the actually measured time series of stability conditions.

3.1.2. Results in South Europe

The performance of the three approaches outlined above has been evaluated in the North Adriatic area, Lavagnini et al. (2003). Seven years of hourly data collected on an oceanographic platform 15 km offshore of Venice and long-term data were available at four coastal stations (Venezia Tessera (VT), Venezia S. Niccolò (VSN), Rimini and Ronchi). Due to the lack of overlapping data periods, all analysis results rely on stationary wind climatology during the last twenty years. The two Venice inland sites lay in front of the platform whereas Ronchi is located around 100 km west and Rimini 150 km south along the North Adriatic coast. Concerning Rimini and Ronchi, the long distance between them and the platform and the different orientation of the costline, have the effect that the two sites are subject to different mesoscale situations i.e. Ronchi is influenced by the Bora, and different local sea-breeze circulation. Therefore, the stations do not fall under the same regional climatology as the platform and neither WAsP nor the other methods are able to reproduce the wind climatology of the platform using Rimini and Ronchi stations. To perform the analysis only data from Venice Tessera and Venice San Niccolò were used.

MCP. This method was found not applicable in this area since satisfying correlations amongst stations could be found neither sector wise nor as a whole.

WAsP. Due to large amount of calms (around 40%) at the two stations, calms were removed when estimating the wind distribution. In WAsP, calms are uniformly distributed in the 12 sectors so that in a region with high frequency of calms, this procedure might modify the sector wise frequency distribution especially in the sectors with low percentage. An exploited alternative was to re-distribute the calms accordingly to the frequency distribution of the wind speed without calms; however, noteworthy differences have not been found. Comparing predicted and experimental mean wind speed and frequency at the platform from VT for 7 years (VT7) and for 35 years (VT35), it was found that, using the VT35 wind distribution the prediction was improved but WAsP overestimates the mean wind speed. Ratios between predicted and observed data were between 0.8 and 1.2. Generally, WAsP underestimates the wind at the platform in the sea sectors and it overestimates in the land sectors.

The Weibull correction method. This method has been applied using 7-year overlapping time series of VT and correcting the A and k wind distribution parameters using the 35 years of VT. The method reproduces well the frequency in all sectors except two, both when wind blows from land, but overestimate the wind speed for all sectors with onshore flow. This is a weakness of the method, which use a long-term experimental wind distribution including its own characteristic climate.

3.2. Methodologies for building offshore climatology from model outputs

1) WAsP® applied to geostrophic wind distributions (GeoWAsP). Geostrophic wind speeds were calculated from a sea level pressure data set [*Benjamin and Miller*, 1990] for the period 1985-1997. WAsP® was applied for each $0.5°x0.5°$ grid of the waters of the European Union assuming any nearby land had roughness length $z_o = 0.03$m. Wind profiles have been predicted for the centre of each grid between 10m and 150m.

2) The Coastal Discontinuity Model (CDM). Geostrophic wind speeds and directions are calculated from the same sea level pressure data set as in GeoWAsP. The CDM works in a slightly different way to WAsP in that geostrophic wind speeds are used to estimate friction velocity assuming a neutral atmosphere for each data point. Hence, instead of applying stability and land-sea corrections to the mean wind speed distribution as in WAsP, the CDM uses air and sea temperature, together with the geostrophic wind speed to calculate the stability parameter (the Monin-Obukhov length) for each grid point at each time step (input data are six-hourly). Air and sea temperatures were given for each 1x1° grid, for the period 1985-1997. Equilibrium land and sea wind speed profiles are corrected for stability. Finally the program uses the fetch distance to land at the centre of the grid point to determine the internal boundary layer (IBL) height and interpolates between equilibrium wind speed profiles over land and sea to the fetch distance accounting for the discontinuity caused in the profile by the IBL.

3.2.1. North European Seas

The main comparison of these methods for Northern Europe was performed as part of the European Commission POWER project e.g. [*Watson, et al.*, 2000] ,[*Watson, et al.*, 2002].

3.2.2. Mediterranean area

Mediterranean areas. A case study: Adriatic Sea

As a general feature, during the central part of the day the wind is enhanced in the coastal areas and reduced at the platform distance. Inverted diurnal cycles with highest wind speed at night have been noted in other offshore locations [*Coelingh, et al.*, 1996], [*Barthelmie, et al.*, 1996]. A number of causes have been postulated including stability effects, the sea breeze and advection.

For the GeoWAsP model the monthly average wind speed from the model is compared to the experimental averages at the platform. The two curves are in agreement showing a minimum in the summer months; however, the average wind speed from CDM is under predicted, especially in winter. Both the sector wise and frequency obtained from the model are in agreement with the experimental values.

CDM was run using input data for grid point 45.5N 12.5E with the fetch distances to the platform calculated by WAsP. The mean wind speed profile was close to neutral but slightly stable with a predicted wind speed of 6.35 m/s at 15 m height. The air-sea temperature difference tends to be large and either positive or negative driving the Monin-Obukhov atmospheric stability parameter to small (i.e. non-neutral) values. The problem derives from the use of the temperature difference to define stability because it is very sensitive to calibration errors or to errors in the databases such as the use of a coastal (mixed land/sea) air temperature with a sea surface temperature. This could be improved using a finer grid but differences in the datasets used for air and sea temperatures would remain.

Similarly geostrophic wind speeds and near-surface winds are highly correlated in exposed areas with strong wind speeds. This strong association between geostrophic and near-surface wind speeds is not realistic for the Mediterranean environment. The model overestimates mean wind speed but the results are promising. Stability at the platform is estimated based on air-sea temperature data sets for the 0.5 by 0.5 degree grid in which the platform is located. Unfortunately this can give errors at the coastline when both land and sea are incorporated into the grid square for the air temperatures.

To conclude, the application of these methodologies in the Mediterranean Sea shows that although for wind speeds greater than 4 ms^{-1} a small correlation could be found, it is not possible to apply the MCP method as a whole. The main drawbacks of using either the CDM or WAsP with geostrophic wind as input are that both models rely on the relationship between the geostrophic wind and the near-surface wind to calculate near-surface wind speeds. If this relationship cannot be predicted, using the drag law for example because conditions close to the surface are stable, or as in this case, because mesoscale circulations such as the sea breeze dominate the local wind climate then the prediction method will not provide a true representation of the near-surface wind resource.

The methods based on WAsP (GeoWAsP and WAsP) are found to give the best results provided that the predictor station lay in an area with similar local circulations.

4. WIND RESOURCE ASSESSMENT USING GCM

Global data sets from General Circulation Models

The data periods of 1 - 3 years are not representative for wind climates of over the 20-30 year lifetime of the wind farms; and homogeneous wind speed time series are rarely available for long periods because most monitored locations have undergone change in landuse and instrumentation. For assessment of trends there are some alternatives: one is to use pressure data sets transformed to the geostrophic wind [*Benjamin and Miller*, 1990] as described for Geo-WAsP and CDM models in the previous section; another solution is to use one of the available reanalysis data sets. The data assimilation procedure "Analysis" integrates measurements taken in a network of measurement points all over the world including meteorological and ship observations and satellite-derived wind speeds for offshore areas to produce the initialization field for the forecast model. All available datasets are assimilated to produce a homogeneous global gridded data set through a model. *Reanalysis* is then performed using a selected "state-of-the-art" Global Circulation Model (GCM) for a long (around 50 years) time-series of consistent meteorological analyses.

There have been two reanalysis programmes that have produced data sets available for research: the first one is from the joint effort of the National Centers for Environmental Prediction, Washington, D.C. and of the National Center for Atmospheric Research, Boulder, Colorado NCEP-NCAR [*Kalnay, et al.*, 1996] and the second is from the European Centre for Medium-range Weather Forecasts, Reading England (ECMWF). For the NCEP-NCAR, this gives a long-time series of data on a 2.5° by 2.5° grid for the whole globe. As an example, based on this data set the wind climate of the Baltic from 1953-1999 shows a general positive trend [*Pryor and Barthelmie*, 2003; *Pryor, et al.*, 2005b]. ECMWF reanalysis datasets include ERA-15 [*Gibson, et al.*, 1997] and ERA-40 [*Uppala, et al.*, 2005] producing data from 1957 to 2001 over a basic resolution of 2.5° by 2.5°. While their resolution is too coarse for direct wind energy application, they can be used to run regional climate models [*Pryor, et al.*, 2005a] (next section).

Data sets from Global Climate Models

Additionally, the Global Climate Model simulations can be used to examine the future climates. Although these typically have low resolutions for direct application, they can be downscaled using either regional climate models [*Pryor, et al.*, 2005a] or statistical approaches [*Pryor, et al.*, 2005c].

4.1 North European Seas

The projections from the present control period using measurements or reanalysis data sets show good agreement for the Nordic region [*Pryor, et al.*, 2006]. The initial results indicated the largest uncertainty was from the GCM used as a boundary condition [*Pryor, et al.*, 2005a] but using later results generated as part of the Intergovernmental Panel on Climate Change e.g. [*Benestad*, 2005] more GCM results are available improving the results [*Pryor, et al.*, 2006].

4.2 Mediterranean area

In 1993, a first study of the wind climatology in a Mediterranean area was performed for the offshore area around Italy [*Lavagnini and Sempreviva*, 1993] using an eight year data set from the ECMWF analyses with a 0.5 x 0.5 degrees grid resolution , and eleven years of radio soundings from 5 Italian stations of the Italian Meteorological Service. The mean wind speed U [ms^{-1}], the scale parameter A [ms^{-1}], and the form parameter k of the Weibull distribution function of the wind speed were calculated for 12 directions of 30 degrees each for all grid points . The radio sounding analyses showed that above 700 hPa no differences in spatial variation of the wind climatology could be identified. This analysis has been extended to the whole Mediterranean Basin resulting in the comparison of different models, satellite and data [*Cavaleri*, 2005; *Sempreviva, et al.*, 2004],[*Cassola, et al.*, 2006],[*Sempreviva, et al.*, 2006], [*Lavagnini, et al.*, 2006].

In *Sempreviva, et al.* (2006) the global climate model of the Laboratory of Dynamical Meteorology of the French CNRS (Coindreau et al. 2006) LMDZOR has been tested against the ECMWF dataset, the GeoWAsP, QuikSCAT and in-situ data in terms of seasonal climatology. LMDZOR is a global atmospheric climate model coupling the finite difference atmospheric general circulation model, LMDZ version 4 and the, land surface scheme ORCHIDEE. The specific feature of the LMDZ model is its Zoom capability, which allows focusing the grid on a particular region, reaching locally a resolution of a few tens of kilometres. In addition, a nudging option recently implemented, allows relaxation of some variables (temperature, wind and humidity) of the model toward analyses or toward fields issued from global scenarios. In Sempreviva et al. (2006), LMDZOR has been run with temperature and wind relaxed toward the ECMWF analyses at a resolution of 100x100 km over the Mediterranean area for year 2000. The time constant of the relaxation varies from 30 minutes outside of the zoomed area to 10 days inside. In this configuration, the climate model simulation can be directly compared to short term observations.
The spatial distribution of the annual mean wind speed shows that the Aegean area is one of the windiest areas in the basin; however, in the summer months, the LMDZ gives wind speeds higher than in winter. To investigate the seasonal variation in different areas, monthly mean wind speed at four experimental locations (the two Italian islands of Lampedusa and Ustica, the offshore platform Venice and the Greek Island of Argos) have been compared to mean monthly wind speeds from QuikSCAT and models estimated at the nearest grid point. While the Italian stations show a yearly cycle of wind speed, which is high during winter and low during summer, the Argos dataset shows a higher wind speed during summer than during winter. QuikSCAT fails to reproduce this feature due to insufficiently resolved island scattered in the Aegean. Also GeoWAsP fails to reproduce the summer maximum suggesting its origin from orography or thermal effects.

5. MESO-SCALE MODELLING

As pointed out in the previous section, the GCM resolutions are too low to resolve the offshore coastal areas; therefore, to assess wind climatology at high resolution, on a vast and complex area, the use of mesoscale models is considered. Mesoscale models resolve the local and regional circulation patterns and the boundary layer in contrast to the current methodologies. The main issue so far has been the computing resources required to run the models, although this can be addressed to some degree by using a compositing approach rather than a time series approach.

5.1 North European Seas

Early model studies were made using the Karlsruhe mesocale model (KAMM) see e.g. [*Adrian, et al.*, 1996]. There were some issues reconciling the model results with observations and other models, possibly due to the model resolution. This was addressed by combining KAMM with the WAsP approach desribed above [*Frank, et al.*, 2001]. Comparison of average wind speeds modelled with WAsP with those obtained by the MIUU mesoscale model indicated good agreement in the central Baltic (within ±3%) but larger differences in near-coastal regions [*Bergström*, 2002]. Due to improvement in the availability of computing resources use of mesoscale models over larger regions has become feasible and is showing good results [*Badger, et al.*, 2006].

In a recent study, the dynamics of the atmosphere of the year 2004 over the German Bight has been simulated with MM5 [Jimenez et al., 2007]. The MM5 model shows promising results with deviation of about 4% offshore. However, the vertical wind speed profile was shown to deviate from the mean wind speed FINO profile. The model results have

also been compared with those of the WAsP model (see 3.1.1.). The largest differences between the two models are found at distances of 5 to 50 km from the coast. While in WAsP the increase occurs in the first 10 km from the coast, MM5 models an increase due to coastal effects for at least 50 km. Since reliable offshore measurements were only available at one distance, the wind speed gradient from coastal to offshore locations could not be investigated. Therefore the authors argue that further validation is necessary, especially for distances between 5 and 50 km from the coast.

5.2 Mediterranean area

Since the 10 m wind field of ECMWF is less accurate near the coast and in narrow basins, due to the low resolution of orography and the land-sea mask, in *Lavagnini, et al.*, (2006) wind statistics were corrected for each grid point, with the statistics of the 2 year Limited-Area Model (LAM) QBOLAM run at 10 km grid size. The QBOLAM model is a parallel version of the finite-difference, primitive-equation, hydrostatic model BOLAM [*Buzzi, et al.*, 1994]. The model domain covers the whole basin with a horizontal grid step of 10 km. Results have been compared with experimental data from buoys, islands and ships in various regions of the basin. This study confirmed that above 700 hPa wind climatology is homogeneous. As expected the difference is higher in coastal areas and enclosed seas up to 20%.

In the Mediterranean area, the surface spatial distribution of wind direction shows channeling effect due to the orography, from Gibraltar along the coast of Africa, in the Sardinia and the Sicily straits. West of the island of Sardinia, the main direction is from northwest in the direction of the Mistral, which maintains its influence down to the southern part of Sicily. East of Sardinia, the wind roses are also influenced by the Tramontana and Sciroc wind regimes. Approaching Gibraltar, wind roses show west-east components following the channeling effect in the strait. Along the coast of Africa main directions change, turning following the orography. In the Adriatic Sea, the effects of the Bora (in the northern part) and Tramontana winds from the north-northeast sectors become predominant.

CONCLUSIONS

The objective of this paper is to present an overview of measurements and modelling techniques which have been used to assess offshore wind resources in Europe over the last twenty years. The availability of new measurement techniques such as Lidar, use of remote sensing and improvements in modelling capabilities present additional, sometimes supporting, measurements for specific site studies. Many sites still require the establishment of a meteorological mast to overcome difficulties of uncertainties in the methods especially relating to small scale spatial variations in the near-coastal zone and to provide detailed wind speed and turbulence profiles.

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