Integrating Offshore Wind and Wave Resource Assessment

M. T. Pontes[1], AM. Sempreviva[2], R. Barthelmie[3], G. Giebel[4], P. Costa[1], A. Sood[5]

[1]INETI, Department Renewable Energies, Estrada do Paço do Lumiar, 1649-038 Lisbon, Portugal
E mail: teresa.pontes@ineti.pt
E-mail: paulo.costa@ineti.pt
[2]Institute of Atmospheric Sciences and Climate, ISAC-CNR, Area di Ricerca CNR, Roma Tor Vergata, Via Fosso del Cavaliere 100, 00169 Rome, Italy
E mail: am.sempreviva@isac.cnr.it
[3]Institute for Energy Systems, School of Engineering & Electronics, The University of Edinburgh, Scotland
E mail: r.barthelmie@ed.ac.uk
[4]Risoe National Laboratory, Department of Wind Energy, Roskilde, Denmark
E mail: gregor.giebel@risoe.dk
[5]ForWind, Center for Wind Energy Research of Universities of Oldenburg and Hannover, Germany
E.mail: abha.sood@forwind.de

Acronyms

BOLAM – Bologna Limited Area Wave Model (CNR-FISBAT)
CNES – Centre National d´Études Spatiales, France
ECMWF – European Centre for Medium-Range Weather Forecast
ESA – European Space Agency
ERA – ECMWF Reanalysis project
IFREMER – French Institute for Exploitation of the Sea
LMDZ – General circulation Model (http://www.lmd.jussieu.fr/)
NCEP – National Centres for Environmental Prediction, USA
NCAR – National Centre for Atmospheric Research, USA
NASA - National Aeronautics and Space Administration
NOAA – National Oceanic and Atmospheric Administration (U.S. Dept. of Commerce)
PSU – Pennsylvania State University
SAR – synthetic aperture radar
WERATLAS – European Wave Energy Atlas

Abstract

The aim of this paper is to review the sources of wind and wave information, the methodologies to assess offshore wind and wave energy resources, and the more relevant results at the European level as a first step to integration of the evaluation of both resources. In situ and remote sensed wind and wave data (using satellite based sensors) are done generally by distinct systems (except for SAR) but numerical atmospheric models and wind - wave models are closely related. Offshore wind resource studies using various types of data are reviewed especially in northern European seas and in the Mediterranean. The wave energy resource assessment at European and national levels is also reviewed and the various atlases are identified.

Keywords: Offshore Wind Resource, Wave Energy Resource, In situ Data, Remote Sensed Data, Meteorological Models, Wave Models

Introduction

Offshore wind farms present benefits that include higher wind resource (larger wind velocities) with lower turbulence levels than adjacent land sites. The joint exploitation of offshore wind and wave energy resources can have a number of advantages that include (i) higher availability of produced power when swells continue after the wind has declined, (ii) higher quality of power delivered to the grid when mixing the power from wind and wave energy; (iii) lower structural and erection costs per MW if the two converters share the same structure; (iv) lower electric cable cost per MW by sharing the same transmission cable, (v) lower operation and maintenance costs and (vi) less area and environmental impact for combined farms. Moreover, the costs of offshore wind exploitation by itself are higher than the onshore ones.
On the other hand, more convenient locations for sitting offshore wind farms are those that are not exposed to rough seas, which are the most appropriate for wave energy utilization.
To start paving the way to the joint exploitation of offshore wind and wave energy, this paper reviews the status of offshore wind wave energy resource assessment with the focus on their integration. In the first section wind and wave climate and energy resource are shortly presented which is followed by a detailed review of the various sources of information

and the respective available sets of data. This is followed by the presentation of methodologies for assessing the wind resource based on non in-situ datasets. A review of numerical atmospheric models and wind-wave models is made focussing the application of results for the characterization of both energy resources. The interrelation of these models is highlighted. Finally a review of wind and wave resource compilation studies and published atlases is presented.

1 Wind and Wave Climate and Resource

Wind resource can be described by mean velocity (speed and direction), and turbulence intensity. However for wind energy the Weibull distribution is typically used:

$$p(U) \equiv \frac{k}{A}\left(\frac{U}{A}\right)^{k-1} \exp\left[-\left(\frac{U}{A}\right)^{k}\right] for\, U \geq 0, A > 0, k > 0$$

where k is a dimensionless shape parameter (a measure of the peakedness of the distribution), A is the scale parameter (a measure of the central tendency), U is the time series of wind speed observations, and p(U) is the probability density function (pdf). Once the A and k parameters are known, moments and percentiles of the wind speed distribution may be computed. For example, the mean of the two-parameter Weibull distribution is:

$$\overline{U} = A\Gamma\left(1+\frac{1}{k}\right)$$

where Γ is the gamma function, see e.g. *Abramowitz and Stegun*, 1979 [1]).
Also once A and k are known the 'expected' energy density (i.e. power in the wind – the wind resource that may be harnessed using wind turbines) is given by:

$$E = \frac{1}{2}\rho A^3\Gamma\left(1+\frac{3}{k}\right).$$

Vertical mean speed profile is used to extrapolate the wind speed to the wind turbines hub-height.

Wave conditions observed at a given point of the sea over a few hours (sea states) are described by its energy density distribution $S(f,\theta)$ (directional spectrum) that is usually summarized by significant wave height H_s, mean (energy) period T_e (T=1/f) or peak period T_p, and mean direction. The flux of energy per unit crest length or wave power P is most relevant parameter for wave energy conversion. In deep water, i.e. where water depth $h \geq L$, L being the wave length (in swell dominated areas such as the North Atlantic for $h \geq 100m$ where waves are not modified by the sea bottom) wave power can be computed by $P \cong 0.5\, H_s^2 T_e$ that is given in kW/m if H_s is expressed in meters and T_e in seconds. It is generally assumed that H_s, T_e, T_p, θ and P pdfs are well fitted by LogNormal distribution as shown e.g. in WERATLAS *(Pontes*, 1998 [2]). However, this distribution is not used such as happens with the Weibull distribution for wind speed. Basic description of wave climate is generally given by bivariate H_s and T_e and/or T_p occurrence scatter tables (joint frequency of occurrence of pairs of height and period parameters) relating to all incoming directions or only to directional sectors. Usual statistics directly describing the waves energy contents are the exceedance of wave power (percentage of time wave power exceeds each power level) in addition to long-term power mean value and the variation coefficient.

2 Wind and Wave Information Sources

The two basic sources of offshore wind and wave information are data obtained from direct or indirect measurement techniques i.e. in-situ or using remote sensing both ground and satellite based, and results of numerical models.

2.1 In-situ Offshore Data

2.1.1 Wind

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[3] and *Tambke et al.*,2005 [4]). Onshore, thermal stability has a daily cycle and in windy cloudy days the assumption of 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 depth decreases 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 [5]).
Prior to 1990, wind speeds were seldom measured offshore for wind energy but rather measurements were made for meteorological services (*Bumke and Hasse*, 1989 [6], *Schmidt and Puttker*, 1991 [7]); on ships (*Graham,* 1982 [8] and *Qualyle,* 1980 [9]) or on oil and gas platforms. Although these have been used to assess wind resource (*Coelingh at al*., 1996 [10] and *Matthies at al*., 1995 [11]) they are typically of insufficient accuracy for the prediction of wind energy from specific sites.
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 [12], *Van Wijk et al.,* 1989 [13]). 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 [4]). 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 [14]), Germany (*Neumann et al.,* 2004 [15]), Sweden (*Ganader et al*., 2001 [16]) 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 [17] and *Barthelmie at a*l., 2003 [18]) and more recently lidar (*Antoniu et al*., 2006[19]).

2.1.2 Waves

In the open ocean deep water wave conditions do not vary significantly within distances of a few hundreds kilometers in large basins such as the North Atlantic, or some tenths in smaller ones such as North Sea and Mediterranean Sea. Long term (at least 10 years) open ocean (deep water) in-situ wave measurements are the most interesting for wave energy utilization.

Waves change as they travel to the coast through waters of decreasing depth due the presence of the sea bottom through various phenomena including refraction, diffraction and reflection, bottom friction and breaking. In the North Atlantic the shallow-water wave modifications changes are most effective in the so-called *nearshore areas* ($h \geq 30m$) where offshore wind farms are being generally located. Shelter by the coastline or by neighboring islands is also an important cause for wave spatial variability. A variety of computational shallow water wave transformation models that generally take also shelter in consideration are available. *Southgate (1993)* [20] presents a review of the various types and underlying assumptions. *Pontes et al. (1993)* [21] includes a survey of the available models and their applicability to wave energy resource assessment. Steady increases in computer power have made possible great increases in accuracy of such models, as well as the capacity to simulate more complex phenomena, e.g. breaking. However, it can be said that no dramatic change in shallow water models has occurred since those studies were done.

Long open-ocean offshore data sets are taken as input to shallow water wave propagation models to compute nearshore /shoreline resource as presented e.g. in *Pontes and Oliveira-Pires* (1992) [22] and *Pontes et al.* (2005) [23].

The first global source of wave data is visual observations carried out for meteorological purposes on board of commercial ships, which started to be archived by 1850 e.g. by British Meteorological Office e.g. *Sherman*, 1984 [24].

The accuracy of visual observation has been assessed by various authors (e.g. *Sherman*, 1983 [25], *Hogben and Lumb,* 1967 [26], *Soares*, 1986 a b[27], [28]). It is considered good for direction, acceptable for wave height and of lower quality for period. In *Quayle and Changery*, 1982 [29] an evaluation of global wave energy resource based on visual observation on board of USA ships between 1971 and 1981 after correction against wind-wave model results (U.S. Corps of Engineers) is presented. Global atlases based on ship observations include *Ocean Wave Statistics* (*Hogben and Lumb,* 1967 [26] and the revised version by *Hogben et al*., 1986 [30]). Long term visual observations data sets are presently more useful to identify whether a certain period of time during which accurate data are available can be considered representative of long term conditions.

For resource assessment long deep-water wave measurements are usually used together with other data types. However, sometimes they are taken alone to assess the resource where other high-quality data sets are not available e.g., the for the preliminary resource assessment in Portugal (*Mollison and Pontes, 1992* [31]), for WERATLAS compilation in the North Sea, Norwegian Sea and Barents Sea, and recently for the detailed resource assessment in the North Sea *(Bells et al., 2007* [32]).

2.2 Satellite Data and Mapping

Sensors such as the altimeter, 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 their use is low frequency of measurements which makes the resource statistics useful only in pre-feasibility studies or in combination with classical offshore measurements and modeling results.

During the last 10 years, the use of satellite spatial and temporal information has been shown to be a valid support for wind and wave energy assessment especially as an instrument to validate modelling efforts.

The two main used observation products for wind resource are SAR (Synthetic Aperture Radar) and scatterometer images. The ESA ERS-1 and ERS-2 satellites carrying radar altimeter and SAR sensors have flown since 1991 and 1995, respectively, being followed by ENVISAT in late 2002. They reach 81.5º latitude repeating at 35-day period, with 0.8º distance between tracks. QuikSCAT scatterometer currently provides the most frequent global coverage with observations twice per day for most of the globe (missing a little near the equator). http://earthobservatory.nasa.gov/Library/QuikSCAT/.

Remote sensed wave data are obtained by radar altimeters that provide accurate H_s data, and SAR from which estimates of directional spectra $S(f,\theta)$ are obtained for long waves with period larger than 8-9s. The NASA/CNES TOPEX/Poseidon (T/P) satellite altimeter was launched in 1992 and was followed by JASON in 2002. The mission has a 10-day repeat period reaching 66º latitude, with 2.8º longitude distance between tracks. The ESA ERS-1 and ERS-2 and ENVISAT referred to above carry radar altimeter and SAR. NASA Geosat Follow-on (GFO) carrying a radar altimeter was launched in 2000. It has a 17 day repeat period the longitude distance between tracks is 1.7º.

The use of SAR spectra can be directly useful for wave energy resource assessment in areas dominated by long swells, but to the authors knowledge this has not been done so far. SAR spectra are being indirectly useful for wave energy resource assessment because they are used in the assimilation procedure for numerical wind-wave models contributing to the increase of their accuracy.

2.2.1 Wind

Various studies on wind resource 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.

The purpose of the EU FP5 "WEMSAR" Project was to provide a tool for offshore wind resource assessment (*Hasager, et al.*, 2005 [33]). 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 model.

In North European Seas, a 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, [34]). In the Mediterranean area, wind climatology using the six years of wind data by QuikSCAT, in terms of spatial variation of wind roses, mean wind speed, seasonal and monthly variation is presented in *Sempreviva, et al.*, (2006, [35]) and compared to wind data from three models (see next sections) i.e. the analyses from ECMWF, the GeoWAsP model, and the Climate Model LMDZ. Generally fair agreement on the monthly and seasonal variation at all sites was found and as expected all models agree best far from the coast.

2.2.2 Waves

Altimeter H_s data are assimilated into global and regional wave models and are also used for validation of such models (see below). For wave energy resource assessment wave period is also crucial. Algorithms for deriving wave period from the altimeter backscatter coefficient have been proposed by *Chalenor and Skoroz* (1984, [36]). In *Davies et al.* (1998, [37]) a model to compute zero-crossing period T_z and T_p was fitted to in situ NOAA data, which showed good accuracy for Portugal west coast. The accuracy of the wave period estimates increased only slightly after fitting the model parameters to local buoy data (*Moreira et al.*, 2002, [38]). This method was used to map the wave energy resource off South America using 1991-2001 T/P data series (*Bruck and Pontes*, *2006* [39]). More recently *Gommenginger et al.* (2003, [40]) proposed a simpler algorithm for wave period.

3. Methodologies for Building Offshore Wind Climatology from non In situ Offshore Data Sets

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, [41]). Following an overview of the different methods used to estimate the wind climatology offshore is presented.

1) The standard measure-correlate-predict (MCP) method. e.g. *Bunn and Watson*, (1996, [42]); *Rogers, et al.*, (2005, [43]) . 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, [44]). 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, [45]) for extrapolating wind data series is based on the concept of modifying the Weibull parameters of the short-term data series to characterize 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 kilometers 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 characterize 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, [46] and [*Korevaar*, 1990, [47]). For the Baltic a comparison between WAsP and a meso-scale model *(Bergström and Barthelmie, 2002*, [48]) 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 [49]) 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 [50]).

A current study in the North Sea using the FINO-1 offshore platform wind data (*Neumann, et al.*, 2004 [15]) 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. 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.

3.1.2. Results in South Europe

The performance of the three approaches outlined above has been evaluated in the North Adriatic area. Seven years of hourly data collected on an oceanographic platform 15 km offshore Venice and long-term data were available at four coastal stations (Venezia Tessera (VT), Venezia S. Niccolò (VSN), Rimini and Ronchi). The platform measurements are hourly values with a calm threshold of 2 ms^{-1}. In the other four selected meteorological stations data were three hourly at the synoptic GMT hours. The main problem is the lack of overlapping data periods; therefore, all analysis results rely on stationary wind climatology during the last twenty years. The two Venice inland sites lay in from 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 coastline, have the effect that the two sites are subject to different meso-scale 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 in total.

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 calms percentage of occurrence. 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 uses 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 [51]) for the period 1985-1997. WAsP® was applied for each 0.5ºx0.5º grid of the waters of the European Union assuming any nearby land had roughness length z_o=0.03m. 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 1x1º 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. Results in North Europe

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 [49] and *Watson, et al.*, 2002 [52]).

3.2.2. Results in South Europe

Mediterranean areas. Case study: Adriatic Sea

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.

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 0.5º by 0.5º 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 due to low correlation coefficients for wind speeds at the predictor and predictand stations. 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 for example using the drag law (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 lays in an area with local circulations similar to the predictand.

4. Wind and Wave Resource Assessment Using Numerical Models

The physics and dynamics of the atmosphere can be described by numerical models that can be implemented at global scale (Global Circulation Model - GCM) or regional/local scale. Created by winds blowing over the sea surface, ocean waves can be described by numerical wind-wave models that solve the equation of transport of the energy density distribution $S(f,\theta)$ taking as input surface wind fields computed by atmospheric models. Solving the energy density balance equation the spectrum is modified locally through a “source” function that represents the energy input from wind, the redistribution of energy due to nonlinear interaction among different frequency components and the energy dissipation caused by breaking or by bottom dissipation.
Such models can be run in Forecast mode using the Forecast wind fields or in Hindcast mode taking the past wind fields. To run atmospheric and wave models in Forecast mode, an assimilation procedure known as *Analysis* (e.g. *Robinson and Lermusiaux*, 2000 [53]) is used to produce the initialization field. Analysis integrates measurements taken in a network of measurement points all over the world. For atmospheric models these measurements include ship wind observations and satellite-derived wind speeds for offshore areas. For wave models in situ and remote sensed (altimeter and SAR) data are used. All available datasets are homogenized through a model. The procedure is complicated and is not discussed here.
Analyses and Forecast Models have been improved both in resolution and in the parameterization of physical processes and have been updated regularly different times over the years. *Reanalysis* procedures have produced long time-series of consistent analyses using a single and state-of-the-art version of the model. Two most relevant reanalysis programmes have produced data sets available for research. These are the reanalysis from the joint effort of the NCEP

and NCAR (*Kalnay, et al.*, 1996 [54]) and the other is from ECMWF. These reanalysis data sets present the advantage of being over a long term period suitable for meaningful climatological analyses. The NCEP-NCAR gives a long-time series of meteorological 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 for the 1953-1999 period shows a general positive trend (*Barthelmie et al.*, 2003 [55]; *Pryor, et al.*, 2005b [56]).

ECMWF reanalysis datasets include ERA-15 (*Gibson, et al.*, 1997 [57]) and ERA-40 producing wind and wave data from 1957 to 2001 over a basic resolution of 1.5° by 1.5° (*Uppala, et al.*, 2005 [58]). In this reanalysis the aerodynamical roughness of the sea surface depending on the sea state is calculated by the wave model. There is a problem with the ERA-40 archives in that wind and waves are underestimated for medium to large values, especially in enclosed areas such as the Mediterranean Sea. This has been reported during the validation exercise by *Caires and Sterl* (2005 [59]). Their work and ways to overcome some of the problems are presented in the online Global Wave Climatology Atlas derived from this 45-year of ECMWF reanalysis data (www.knmi.nl/waveatlas).

The resolution of global atmospheric models is in general too coarse for wind speeds and wave results to be used directly in the majority of applications; they can be downscaled using either regional models or statistical approaches. For wind applications see *Pryor, et al.* (2005a, [60]) and *Pryor, et al.*,(2005c [61]).

4.1 Wind

4.1.1 Global Atmospheric Models

In North European Seas results have shown that in general, projections from the control period of Global Atmospheric Models (GAM) which can be compared to measurements or reanalysis data sets show good agreement for this region (*Pryor, et al.*, 2006 [62]). The initial results indicated the largest uncertainty was from the GAM used as a boundary condition (*Pryor, et al.*, 2005a [60]) but using later results generated as part of the Intergovernmental Panel on Climate Change e.g. (*Benestad*, 2005 [63] more GAM results are available improving the results (*Pryor, et al.*, 2006 [62]).

In the Mediterranean area, a first study of the wind climatology was performed limited to the offshore area around Italy (*Lavagnini and Sempreviva*, 1993 [64]) using a data set of eight years from the analyses of the ECMWF with a grid resolution of 0.5º x 0.5º, and eleven years of radiosoundings from 5 Italian stations. This 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 since 2002 resulting in the comparison of different models, in-situ and satellite data (*Cavaleri*, 2005 [65]; *Sempreviva, et al.*, 2004 [66], *Cassola, et al.*, 2006 [67], *Sempreviva, et al.*, 2006 [35], *Lavagnini, et al.*, 2006 [68]).

4.1.2 Meso-Scale Models

Meso-scale models resolve the local and regional circulation patterns and the boundary layer in contrast to the current methodologies.

In the North European Seas, early model studies were made using the Karlsruhe meso-scale model (KAMM) see e.g. *Adrian, et al.* (1996 [69]). 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 described above (*Frank et al.*, 2001 [70]). Comparison of average wind speeds modelled with WAsP with those obtained by the MIUU mesoscale model (**www.geo.uu.se/luva**, Uppsala University) indicated good agreement in the central Baltic (within ±3%) but larger differences in near-coastal regions (*Bergström*, 2002 [71]). Due to improvement in the availability of computing resources use of meso-scale models over larger regions has become feasible and is showing good results (*Badger, et al.*, 2006 [72]). More recently, the numerical weather prediction model, such as WRF (*Sood, et al.,* 2007, [73]) MM5, REMO etc., using global analysis and reanalysis as initial and lateral boundary conditions, has been integrated to reconstruct the wind field over the entire domain where the local measurements serve to control the quality of the resource assessment. The simulations focussed on the North Sea have shown only very small deviations of about 1.8% compared to in-situ measurements at 100 m height.

In southern Northeast Atlantic off Portugal the first Offshore Wind Potential Atlas for the whole west and south coastal regions based on PSU/NCAR MM5 meso-scale model (grid 3x3km) was developed (*Costa et al., 2006* [74]). GIS software was used to select the best coastal sites to develop offshore wind parks as a first approach. The resource data were simulated ingesting one year NCAR - NCEP reanalysis data into the MM5 model at 6h intervals. Two wind turbines (a 60m –high 1500 kW and a 2000kW at 80m) were considered. The wind and energy density fields were corrected by an intra-annual variability factor obtained from 12-year data measured by four anemometric reference stations. The restrictions considered to compute the technical resource refer to turbines hub-height (higher than 60m), distance to shore, sea bed slope, water depth (up to 40m), and the exclusion of navigation channels. In the central west coast, the Berlengas area presents the best resource for both turbines the wind potential ranging from 3000 to 3700h/year. This led to an undergoing monitoring campaign that will enable a complete validation of the previous results. In addition, an offshore wind energy resource assessment that will include both long-term high resolution meso-scale simulations and micro-scale (WAsP) model results is being prepared.

In the Mediterranean area, wind statistics produced by the ECMWF atmospheric model were corrected for each grid point with the statistics produced using 2-

year runs of the mesoscale model QBOLAM (a parallel version of the model BOLAM (*Buzzi, et al.*, 1994 [75]), at a grid size of 10km (*Lavagnini, et al.*, 2006 [68]). Results have been compared to experimental data from buoys, islands and ships in various regions of the basin. Maps of mean wind speeds and Weibull parameters have been produced to illustrate the results. This study also confirmed that above 700 hPa wind climatology is homogeneous. As expected the difference is higher in coastal areas and enclosed seas up to 20%. *Cassola et al.*, (2006 [67]) have produced an Italian Offshore Wind Atlas. The wind fields above sea at different heights all along the Italian coast of the Mediterranean Sea have been computed through a procedure that combines statistical analyses of wind speed aloft with numerical modeling of wind flows offshore. The comparison of the mean wind speed in different Italian offshore areas to wind speed resulting from *Lavagnin, et al.*, (2006 [68]) shows in average lower values of the former with respect to the latter.

4.2 Waves

The most update and generally used are *third generation* models with an explicit representation for the physical processes relevant for wave evolution, namely the non-linear interactions. The WAM Model (*The WAMDI Group*, 1988 [76]) was firstly implemented at ECMWF being described by *Komen et al*.,(1994 [77]). It was further implemented in many centers. WAVEWATCH III (WW3) developed by NOAA/NCEP differs in governing equations, numerical methods and physical parameterizations. Verifications and intercomparisons of wave models has shown that model accuracy has continuously increasing namely due to data assimilation and statistical forecasts (ensemble prediction), its accuracy being presently limited by the quality of input wind fields (*Janssen*, 2006 [78]).

At ECMWF the atmospheric and WAM models are coupled, i.e., for each forecast the models are run twice. In the second run of the atmospheric model, sea surface roughness computed from wave field produced by WAM first run, are used to describe more accurately sea roughness, producing in this way more accurate wind fields that are taken as input in the WAM second run. The grid resolution of global and a European WAM models are 0.5 x 0.5º and 0.25ºx0.25º, respectively. Global in situ and satellite data are assimilated. Results for deterministic and ensemble forecasts are produced. Global and regional atmospheric and WAM models are also operationally run at German meteorological office Deutcher Wetterdienst (DWD). There, global and regional (central Europe and surrounding areas) meteorological models are operationally run as well as global WAM model and regional versions for Mediterranean Sea and North, Baltic and Adriatic Seas. The Danish Meteorological Institute (DMI) runs WAM for several regions (North Atlantic, 0.5º x 0.5º), North and Baltic Seas, inner Danish waters and Med Sea. In Ireland the Meteorological Irish Office runs a regional version (0.2ºx0.25º), nested into ECMWF WAM. In Spain at Clima Maritimo (Puertos del Estado) nested versions for the Atlantic area (grid from 3 x 3 km offshore until 0.25º x 0.25º onshore), and for Mediterranean and Cantabric coasts are run. The Instituto de Meteorologia (IM) in Portugal, runs MAR3G (third generation model coupled to a shallow water model, *Oliveira Pires*, 1993 [79] and further updated) for mainland and Azores and Madeira regions. In the UK Met Office their atmospheric and second generation wave model (*Golding*, 1983 [80] and further updated) runs in global and regional versions.

Wave climate and wave energy resource atlases have compiled from results of these models using also in situ and satellite data. The European Wave Energy Atlas WERATLAS was the first attempt to characterize the offshore European resource using a common methodology and homogenized wave data sets. It contains monthly, seasonal and annual wave power roses and bivariate scatter tables and power exceedance curves. Except in the North Sea, Norwegian Sea and Baltic Sea were long term in situ data were available, ECMWF WAM model results were used. The selection of this model and verification of the results used in the atlas compilation were based on comparison against in situ (buoy) and T/P and Geosat satellite altimeter data. It was found that in the North Atlantic the WAM results were very good but the quality was poorer in Mediterranean Sea probably due to lower quality of wind fields (*Pontes et al*., 1997 [81]). Higher resolution atmospheric and wave models for this area were further implemented. The ONDATLAS is a nearshore atlas for mainland Portugal (*Pontes et al*., 2005 [82]) and Madeira islands (www.aream.pt). It was compiled from results of MAR3G model using the same methodology as WERATLAS. The Atlas of UK Marine Renewable Energy Resources (*ABP MER*, 2004 [83]) describes the wave and tidal energy resources in the British continental self. The wave resource is based on the UK Met Office wave model results. The Irish Accessible Wave Energy Resource Atlas (*ESBI*, 2005 [84]) is based on results of the WAM run at Danish Meteorological Institute calibrated by buoy data. It describes the theoretical, technical energy resource (electrical power produced by a wave energy converter), and the accessible energy resource (disregarding exclusion zones)

Acknowledgment

The project is funded by the European Commission (019898(SES6)). RB acknowledges support from the Scottish Funding Council and the Edinburgh Research Partnership.

REFERENCES

[1] Abramowitz , M. and I. Stegun, Handbook of Mathematical Functions, Dover, New York, 1979.

[2] Pontes, M.T., “Assessing the European Wave Energy Resource”. *Journal of Offshore Mechanics and Arctic Engineering*, vol. 120, p.226-231, 1998.

[3] Gryning, S. E., E. Batchvarova, B. Brümmer, H. E. Jørgensen, and S. E. Larsen, On the extension of the wind profile over homogeneous terrain beyond the surface boundary layer, *Boundary-Layer Meteorology*, Accepted, 2007.

[4] Tambke, J., M. Lange, U. Focken, J. Wolff, and J. Bye, Forecasting offshore wind speeds above the North Sea, *Wind Energy*, 8, 3-16, 2005.

[5] Barthelmie, R. J., Evaluating the impact of wind induced roughness change and tidal range on extrapolation of offshore vertical wind speed profiles, *Wind Energy*, 4, 99-105, 2001a.

[6] Bumke, K., and L. Hasse, An analysis scheme for determination of true surface winds at sea from ship synoptic wind and pressure observations., *Boundary-Layer Meteorology*, 47, 295-308, 1989.

[7] Schmidt, H., and J. Puttker, Wind and wave conditions in 55 European coastal sea areas, determined from weather and wave observations of voluntary commercial ships., Deutscher Wetterdienst Seewetteramt,, Hamburg, Germany, 1991.

[8] Graham, A. E., Winds estimated by the Voluntary Observing Fleet compared with instrumental measurements at fixed positions. *Meteorological Magazine*, vol. 1325, 312-326, 1982.

[9] Quayle, R. G., Climatic comparisons of estimated and measured winds from ships. *Journal of Applied Meteorology*, vol. 19, 142-156, 1980.

[10] Coelingh, J. P., A. J. M. van Wijk, and A. A. M. Holtslag, Analysis of wind speed observations over the North Sea. *Journal of Wind Engineering and Industrial Aerodynamics*, 61-51, 1996.

[11] Matthies, H. G., A. Garrad, N. Scherweit, C. Nath, M. A. Wastling, T. Siebers, T. Schellin, and D. C. Quarton, Study of offshore wind energy in the EC, Verlag Natürliche Energie, Brekendorf, 1995.

[12] Motta, M., R. J. Barthelmie, and P. Vølund, The influence of non-logarithmic wind speed profiles on potential power output at Danish offshore sites., *Wind Energy*, 8, 219-236, 2005.

[13] Van Wijk, A. J. M., A. C. M. Beljaars, A. A. M. Holtslag, and W. C. Turkenburg, Diabatic wind speed profiles in coastal regions. Paper presented at *EWEC 1989*, Glasgow.

[14] Barthelmie, R., O. Hansen, K. Enevoldsen, J. Højstrup, S. Larsen, S. Frandsen, S. Pryor, M. Motta, and P. Sanderhoff , Ten years of meteorological measurements for offshore wind farms. *Journal of Solar Energy Engineering*, 127(2), 170-176, 2005.

[15] Neumann, T., K. Nolopp, and K. Herklotz , First operating experience with the Fino1 research platform in the North Sea, *DEWI Magazin*, 24, 27-32, 2004.

[16] Ganader, H., S. Dahlman, G. Ronsten, and H. Bergstrom, Medium term evaluation of meteorological conditions, power performance and loads on the first swedish offshore wind farm at Bockstigen, Paper presented at *European Wind Energy Association Offshore Wind Energy Conference*, Brussels, 4 pp, 2001.

[17] Coelingh, J., L. Folkerts, and E. van Zuylen, Offshore sodar measurements - 1 year experience, paper presented at *Offshore wind energy in Mediterranean and other European Seas*, *ENEA*, Naples, 51-64, 2003.

[18] Barthelmie, R. J., L. Folkerts, F. Ormel, P. Sanderhoff, P. Eecen, O. Stobbe, and N. M. Nielsen (2003), Offshore wind turbine wakes measured by SODAR, *Journal of Atmospheric and Oceanic Technology*, 30, 466-477.

[19] Antoniou, I., H. Jørgensen, T. Mikkelsen, S. Frandsen, R. Barthelmie, C. Perstrup, and M. Hurtig (2006), Offshore wind profile measurements from remote sensing instruments, paper presented at *European Wind Energy Association Conference*, Athens, Greece, February 2006, 10 pp.

[20] Southgate, H .N., "The use of wave transformation models to evaluate inshore wave energy resource", *Proc. First European Symposium on Wave Energy*, pp. 41-46. Edinburgh, Scotland, 1993.

[21] Pontes, M. T.; Mollison, D.; Cavaleri, L.; Nieto, J. C.; Athanassoulis, G. A. "Wave Studies and Development of Resource Evaluation Methodology. Final Report.", DGXII Contract Nº JOUR-0132-PT(MNRE), 75pp, and "Evaluation of the Wave Energy Resource", *Proc. Wave Energy R&D Workshop*, Cork, 1-2 October 1992, eds. G.Caratti, A.T. Lewis e D. Howett, DGXII Rept. Nº EUR-15079 EN, pp.1-8, 1993.

[22] Pontes, M.T. and Oliveira-Pires, H., Assessment of shoreline wave energy resource", *Proc. Second Int. Offshore Mechanics and Polar Engng. Conf. (ISOPE'92)*, Vol. 1, pp. 557-562. San Francisco, USA, Eds. J. S. Chung, B. J. Natvig, Y. Li and B. M. Das, 1992.

[23] Pontes, M. T., Cândido, J., Henriques, J.C.C., Justino, P.A.P, "Optimizing OWC Sitting in the Nearshore", *Proc. 6th European Wave and Tidal Energy Conference*, Glasgow, Scotland, 2005.

[24] Sherman, R.J., The availability of wind and wave data from the UK Meteorological Office ". Proc. Int. Symp. Wave and Wind Climate Worldwide, *The Naval Institution of Naval Architects* (RINA), London, 1984.

[25] Sherman, R.J., The Meteorological Office main marine databank, *Marine Observer*, vol. 53, 208-217, 1983.

[26] Hogben, N. and Lumb, F.E., Ocean Wave Statistics, *HMSO*, London, 1967.

[27] Soares, C. G., Assessment of the uncertainty in visual observations of wave height, *Ocean Engng*., vol. 13, 37-56, 1986a

[28] Soares, C. G., Calibration of visual observations of wave period, *Ocean Engng*., vol. 13, 539-547, 1986b

[29] Quayle, R. G. and M. J. Changery, Estimates of coastal deepwater wave energy potential for the world, *Proc. Ocean 81 Conf.*, Boston, 1, 903-907, 1982.

[30] Hogben, N. Dacunha and Ollivier, Global Wave Statistics, *Unwin Brothers*, London, 1986.

[31] Mollison, D. and Pontes, M.T., Assessing the Portuguese wave power resource, *Energy-Pergamon*, vol. 17, Nº3, 55-268, 1992.

[32] Beels, C., J.C.C. Henriques, J. De Rouck1 and M.T. Pontes, Wave energy resource in the North Sea, submitted to *7th EWTEC*, *Porto*, September 2007.

[33] Hasager, C. B., M. Nielsen, P. Astrup, R. Barthelmie, E. Dellwik, N. O. Jensen, B. Jørgensen, S. Pryor, O. Rathmann, and B. Furevik, , Offshore wind resource assessed from satellite SAR wind field maps, *Wind Energy*, 8, 403-419, 2005.

[34] Hasager, C. B., R. Barthelmie, M. Christiansen, M. Nielsen, and S. Pryor, Quantifying offshore wind resources from satellite maps: study area the North Sea, *Wind Energy*, 9, 63-7, 2006.

[35] Sempreviva, A. M., B. Furevik, R. J. Barthelmie, F. Cheruy, B. Jimenes, and C. Transerici (2006), Offshore wind energy potential in the Mediterranean Basin. In *Proceedings of the Conference Offshore Wind Energy in Mediterranean and Other European Seas*, *OWEME*S, Civitavecchia, Italy 19-21 April 2006, Available on CD ROM.

[36] Chalenor, P..G. and M.A Skroroz. Extraction of wave period from altimeter data, in *European Space Agency*, (Special Publication), ESA SP, 1984.

[37] Davies, C.G., P.D. Cotton, Challenor e D.J. Carter. On the measurements of wave period from radar altimeters, ocean wave measurements and analysis, *Proc. 3rd Int. Symp. Waves'97, ASCE*, Reston, VA, pp 819-826, 1998.

[38] Moreira, N.M.,H. Oliveira Pires, T. Pontes e C. Câmara, Verification of TOPEX-Poseidon wave data against buoys off the West Coast of Portugal. *Proc. Conference on Offshore Mechanics and Arctic Engineering (OMAE02),* paper 2002-28254. Oslo, Norway, 23 - 28 June, 2002.

[39] Bruck, M. and Pontes, M.T., Wave energy resource assessment based on satellite data, *Workshop on Performance Monitoring of Ocean Energy Systems*, (http://pmoes.ineti.pt), Lisbon, November 2006.

[40] Gommerginger, C.P., M.A. Srokosz, P.G. Challenor, P. Cotton. An empirical model to retrieving ocean wave period from nadir altimeter data. In *Geoscience and and Remote Sensing Symposium (IGARSS),* 2003.

[41] Barthelmie, R. J., Modelling and measurements of coastal wind speeds, in *Renewable Energy: Trends and Prospects,* edited by S. K. Majumdar, et al., Pennsylvania Academy of Science, Easton, PA, 2001b.

[42] Bunn, J. C., and S. J. Watson, A new matrix method of predicting long-term wind roses with MCP, paper presented at *European Union Wind Energy Conference*, May 1996, H.S. Stephens and Associates, Bedford, UK, Goteborg, Sweden, 588-591, 1996.

[43] Rogers, A., J. Rogers, and J. F. Manwell, Comparison of the performance of four measure-correlate-predict algorithms, *Journal of Wind Engineering and Industrial Aerodynamics*, 93, 243-264, 2005.

[44] Mortensen, N. G., D. N. Heathfield, L. Myllerup, L. Landberg, and O. Rathmann, Wind Atlas Analysis and Application Program: WAsP 8 Help Facility, Risø National Laboratory, Roskilde, Denmark. 335 topics. ISBN 87-550-3457-8, DOI, 2005 http://www.risoe.dk/vea/projects/nimo/WAsPHelp/Wasp8.htm.

[45] Højstrup, J. and Middelgrunden. Beregning af vind resourcen baseret på on-site målinger okt-dec 1997, Internal, 17pp., Risø National Laboratory, Roskilde, Denmark, 1998.

[46] Børreson, J. A. Wind Atlas for the North Sea and the Norwegian Sea, 346 pp., *Norwegian University Press*, Oslo, 1987.

[47] Korevaar, C. G., North Sea Climate., ISBN 0-7023-0664-3 ed., 152 pp., *Kluwer Academic Publishers*, 1990.

[48] Bergström, H., and R. J. Barthelmie, Offshore boundary-layer modelling, paper presented at *2002 Global Windpower*, *EWEA*, Paris, 2002.

[49] Watson, G., J. Halliday, J. Palutikof, T. Holt, R. Barthelmie, J. Coelingh, L. Folkerts, G. Wiegerinck, E. van Zuylen, J. Cleijne, and G. Hommel, POWER -A methodology for the prediction of offshore wind energy resources, paper presented at Proceedings of *OWEMES (Offshore Wind Energy in Mediterranean and Other European Seas)* conference, ATENA/ENEA, Sicily, 111-122, 2000.

[50] Petersen, E. L., Wind resources of Europe (the offshore and coastal resources), paper presented at *EWEA Special Topic Conference '92*, September 8-11 1992, Herning, Denmark, 1992.

[51] Benjamin, S. G., and P. A. Miller , An alternative sea level pressure reduction and a statistical comparison of geostrophic wind estimated with observed surface winds., *Monthly Weather Review*, 118, 2099-2116, 1990.

[52] Watson, G., J. Halliday, R. Brownsword, J. Palutikof, T. Holt, R. Barthelmie, J. Coelingh, E. van Zuylen, and J. Cleijne. Predicting offshore wind energy resources. Final report to the European Community on Contract JOR3-CT98-0286., Rutherford Appelton Laboratory, Didcot, UK, 2002.

[53] Robinson, A. R. and P. F.J. Lermusiaux, Overview of Data Assimilation, Harvard Reports in Physical/Interdisciplinary Ocean Science, Number 62, The Division of Engineering and Applied Sciences, Harvard University, Cambridge, Massachusetts, August 2000.

[54] Kalnay, E., M. Kanamitsu, R. Kistler, W. Collins, D. Deaven, et al., The NCEP/NCAR 40-year Reanalysis Project, *Bulletin of the American Meteorological Society*, 77, 437-470, 1996.

[55] Barthelmie, R. J., L. Folkerts, F. Ormel, P. Sanderhoff, P. Eecen, O. Stobbe, and N. M. Nielsen. Offshore wind turbine wakes measured by SODAR, *Journal of Atmospheric and Oceanic Technology*, 30, 466-477, 2003.

[56] Pryor, S. C., R. J. Barthelmie, and J. T. Schoof The impact of non-stationarities in the climate system on the definition of 'a normal wind year': A

case study from the Baltic., *International Journal of Climatology*, 25, 735-752, 2005b.

[57] Gibson, J. K., P. Kållberg, S. Uppala, A. Hernandez, A. Nomura, and E. Serrano, ERA Description, *Re-Analysis (ERA) Project Report Series*, 72 pp, *ECMWF*, Reading, 1997.

[58] Uppala, S. M., P. W. Kållberg, A. J. Simmons, U. Andrae, V. da Costa Bechtold, et al., The ERA-40 re-analysis, *Quarterly Journal of the Royal Meteorological Society*, 131, 2961-3012, .2005.

[59] Caires, S., and A. Sterl. A new non-parametric method t correct data: Application to significant wave height from the ERA-40 reanalysis. *J. Atmospheric and Oceanic Tech.*, 22 (4), 443-459, 2005.

[60] Pryor, S. C., R. J. Barthelmie, and E. Kjellström, Analyses of the potential climate change impact on wind energy resources in northern Europe using output from a Regional Climate Model, *Climate Dynamics*, 25, 815-835, 2005a.

[61] Pryor, S. C., J. T. Schoof, and R. J. Barthelmie, Empirical downscaling of wind speed probability distributions, *Journal of Geophysical Research*, 110, doi: 10.1029/2005JD005899, 2005.

[62] Pryor, S. C., J. T. Schoof, and R. J. Barthelmie, Winds of Change? Projections of near-surface winds under climate change scenarios, *Geophysical Research Letters*, 33, doi:10.1029/2006GL026000, 2006.

[63] Benestad, R. E., Climate change scenarios for northern Europe from multi-model IPCC 4AR climate simulations, *Geophysical Research Letters*, 32, doi: 10.1029/2005GL023401, 2005.

[64] Lavagnini, A., and A. M. Sempreviva, Wind climatology between 950 and 500hPa over the Mediterranean area above Italy, *Il Nuovo Cimento*, 16, 131-140, 1993.

[65] Cavaleri, L., The wind and wave atlas of the Mediterranean Sea – the calibration phase, *Advances in Geosciences* 2, 255–257, 2005.

[66] Sempreviva, A. M., B. Furevik, and R. Barthelmie, Offshore wind resource in the Mediterranean, paper presented at *European Wind Energy Conference*, Proceedings on CD, London, November 2004

[67] Cassola, F., M. Burlando, L. Villa, P. Latona, and C. Ratto (2006), Evaluation of the offshore wind potential along the Italian coasts, paper presented at In Proceedings of the conference, *Offshore Wind Energy in Mediterranean and Other European Seas*, *OWEMES*, Civitavecchia, Italy 19-21 April 2006. Available on CD ROM.

[68] Lavagnini, A., A. M. Sempreviva, C. Accadia, M. Casaioli, S. Mariani, T. C., and A. Speranza, Comparison of the wind climatology offshore in the Mediterranean Basin from three models, *Wind Energy*, 9, 251-266, 2006.

[69] Adrian, G., N. Dotzek, and H. Frank, Influence of thermally induced wind systems on the wind climate of the Baltic Sea analysed by numerical simulations., paper presented at *European Union Wind Energy Conference*, H.S. Stephens and Associates, Bedford, UK, Goteborg, 1996.

[70] Frank, H., O. Rathman, N. Mortensen, and L. Landberg, The numerical wind atlas - the KAMM/WasP method, ISBN 87-550-2909-4. Risø-R-1252(EN), 2001 http://www.risoe.dk/rispubl/VEA/ris-r-1252.htm, Risø National Laboratory, Roskilde, Denmark

[71] Bergström, H., and R. J. Barthelmie (2002), Offshore boundary-layer modelling, paper presented at *2002 Global Windpower*, *EWEA*, Paris

[72] Badger, J., R. Barthelmie, S. Frandsen, and M. Christiansen (2006), Mesoscale modelling for an offshore wind farm, paper presented at European *Wind Energy Association Conference*, Athens, Greece, February 2006.

[73] Sood, A, K. Suselj, D. Heinemann (2007) Wind resource assessment in the German Bight: extreme winds at Meso- and microscale, paper presented at *European Wind Energy Conference*, Proceedings on CD, Milan, November 2007.

[74] Costa, P. , Estanqueiro, A., Miranda, P., Building a Wind Atlas for Mainland Portugal using a weather type classification, *Proc. European Wave Energy Conf.*, Athens, Greece, 2006.

[75] Buzzi, A., M. Fantini, P. Malguzzi, and F. Nerozzi , Validation of a limited area model in cases of Mediterranean cyclogenesis: surface fields and precipitation scores, *Meteorology and Atmospheric Physics*, 53, 53-67, 1994.

[76] The WAMDI Group, "The WAM model – third generation ocean wave prediction model", *J. Phys.* Oc., vol 18, 1775-1810, 1988.

[77] Komen, G., L. Cavaleri, M. Donelan, K. Hasselmann, S. Hasselmann and P.A.E.M. Janssen, *Dynamics and Modelling of Ocean Waves*, Cambridge Univ. Press, 532 pp., 1994.

[78] Janssen, P. A.E.M., Progress in Ocean Forecatsing at ECMWF, personal communication, 2006.

[79] Oliveira-Pires, H., Numerical Modeling of Wind-Generated Waves, Ph.D. Thesis, Instituto Superior Técnico, Lisbon Technical University, 1993.

[80] Golding, B., A wave prediction model for real-time sea-state forecasting, *Q. J. Royal Met. Soc.*, vol. 109, 393-416, 1983.

[81] Pontes, M. T, S. Barstow, L. Bertotti, L. Cavaleri, H. Oliveira-Pires, "Use of numerical wind-wave models for assessment of the offshore wave energy resource". *Journal of Offshore Mechanics and Arctic Engineering*, vol. 119, p.184-190, 1997.

[82] Pontes, M.T., R. Aguiar and H. Oliveira-Pires, The nearshore wave energy resource in Portugal", *Journal Offshore Mechanics and Arctic Engineering*, Vol. 127., Nº. 3, 249-255, 2005.

[83] ABP Marine Environmental Research Ltd., *Atlas of UK marine renewable energy resources: Technical report*". Department of Trade and Industry, UK, 2004.

[84] ESBI International, "Accessible Wave Energy Resource, Atlas: Ireland: 2005", *Marine Institute and Sustainable Energy Ireland*, 2005.