Laboratório Nacional de Energia e Geologia, I.P.

UNIDADE DE ENERGIAS RENOVÁVEIS E INTEGRAÇÃO
DE SISTEMAS DE ENERGIA

PLANNING THE USE OF OFFSHORE RENEWABLE ENERGY IN PORTUGAL

D 2.1 – Methodologies to assess the renewable offshore resources

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Abstract

The present document was prepared by Laboratório Nacional de Energia e Geologia, I.P. (LNEG) as part of the R&D activities of the project OffhorePlan. According to the activities plan of Task 2 – "Mapping of available renewable resource", this report presents the methodologies established to assess the Portuguese offshore wind and wave energy potential. This procedure and the outcome of the offshore energy resource assessment in the Portuguese coast are crucial steps to establish a strategic plan for the exploitation of marine renewable energies in Portugal.

In the scope of the project, a new high-resolution offshore wind resource atlas will be developed - this report provides a description of the methodology that will be applied to achieve that goal. The methodology is based on atmospheric mesoscale numerical modelling simulations using state-of-the-art atmospheric parameterizations in order to deal with the wind flow behaviour phenomena near the ground, the sea surface, and the land-sea border. In order to produce an accurate offshore wind atlas, a data assimilation technique will be tested to assess the model performance. An experimental campaign will take place during this project allowing a full validation of the results obtained. The final offshore wind atlas for the Portuguese seashore will be converted into a format compatible with the most used geographic information system platforms and disseminated through; 1) other project tasks that depend on the offshore wind atlas and 2) wind industry and policymakers.

In what concerns wave resource, data from two databases will be collected, namely, ONDATLAS, and PEMAP, in order to identify the Portuguese coastal areas more suitable for wave energy devices deployment. The data obtained from these two databases will be complemented with buoy data from Instituto Hidrográfico (IH) operating along the Portuguese coast. Statistics for several parameters of the sea state will be presented, such as, significant height, peak period, mean wave power, and others, that are used for the characterization of the wave resource.

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Table of contents

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1. Introduction

The present report was developed by LNEG as part of the R&D activities of the project OFFSHORE-Plan. According to the activities plan for Task 2 – "Mapping of available renewable resource", the main objective of this report is to present a description of the methodologies that will be applied to perform the offshore wind and wave resource assessment.

In the scope of this project, a methodology based on a numerical weather prediction (NWP) model resorting to the MM5 model (Grell et al. 1994; Skamarock et al. 2008) is proposed to improve the 5 km x 5 km offshore wind atlas obtained in (Costa 2004; Costa and Estanqueiro 2004; Costa et al. 2006). Currently, the most applied NWP models in the wind sector are the Weather Research and Forecasting (WRF) (Wei et al. 2009) and the Mesoscale Fifth Model (MM5) (Grell et al. 1994; Skamarock et al. 2008).The extensive use of these models can be explained by i) their capabilities to perform accurate near surface atmospheric phenomena simulations (Liu and Warner 2004) and ii) the free availability to public use. Recent studies have shown that the MM5 model has a i) higher onshore capability to predict the planetary boundary layer (PBL) height, and, consequently, a better characterization of wind speed and direction (Liu and Warner 2004) and ii) slightly better performance in the wind offshore assessment (Salvação et al. 2014). Therefore, and benefiting from the structure developed to generate the first offshore wind atlas as well as the previous literature, the MM5 model was selected to obtain the high-resolution (1km x 1 km) offshore wind atlas.

The improvement of the previous 5km x 5km Atlas is a crucial step to allow a sufficiently detailed spatial planning of the marine energy resources for the Portuguese continental area. In this project, the improvement strategy is related to: a) spatial resolution (1km x 1km); b) initial and boundary condition (IBC) data; and c) data assimilation methodology. The wind atlas methodology is based on atmospheric mesoscale numerical modelling simulations using state-of-the-art atmospheric parameterizations in order to deal with the wind flow behaviour phenomena near the ground, sea surface and the land-sea border. The model simulations will be fed by initial and boundary conditions (IBC) data. Using the common metrics statistics (e.g., Pearson correlation) and observational data, different reanalysis/analysis will be tested to identify the most suitable IBC data to feed the model. The observational data are gathered from different measurement systems, namely, synoptic stations, radio-soundings, buoys, coastal anemometric masts, ZephIR instruments – vertical and horizontal wind profilers – as well as sea surface winds inferred by satellites. These observational data will also be used to evaluate the performance of

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the mesoscale model simulations, and will allow the identification of the most suitable parameterizations. In order to produce a reliable offshore wind atlas, a data assimilation technique will be tested to inquire the model performance. The data assimilation technique is coupled into model's equations and an independent wind database from the observational wind data will be used to evaluate the benefit from the data assimilation procedures. In case wind estimates tend to worsen with the use of data assimilation technique, then the data assimilation technique will be uncoupled from the model's equations.

In order to obtain the Portuguese wave resource, ocean and wave data from two databases – ONDATLAS, Atlas do Recurso Energético (Pontes et al. 2005a) and PEMAP, Potencial de Energia Marinha em Portugal (Pontes et al. 2005b) – are collected in order to identify the areas on the Portuguese coast that are most suitable for the deployment of wave energy devices. The ONDATLAS database presents the mean wave information feature for a set of 81 places located in intermediate or deep waters. Statistical data will be processed and presented for several parameters of the sea state and wave information such as the significant height, peak period, mean wave power, and others, which are used to characterize the wave resource. It should be noticed that the data included in ONDATLAS database are validated. For offshore sites, data from buoys will be used and for sea regions located in intermediate water depths, data from numerical models, e.g., Mar3G (Oliveira Pires (IPMA) 1993) will be used. In the case of PEMAP database, specific information based on the seabed slope, tectonic faults, ports, sea corridors, submarine cables, defence areas, among others, will be used. The combination of data from both databases will enable the development of maps identifying the most suitable zones, in terms of energy resource, using information on existing restrictions to the wave device deployment. Data from boys operated by Instituto Hidrográfico (IH) will also be used to complement the databases.

Section 2 provides a brief literature review regarding offshore wind and wave resource assessment, while section 3 describes the methodologies that will be applied in the scope of this project. Finally, in section 4 some final remarks are provided.

2. Relevant work on offshore maritime resource assessment

2.1. Wind resource assessment

Several studies have been developed in order to produce regional or national wind atlases being the most popular the European Wind Atlas (Troen and Petersen 1989). This study, coordinated by DTU-RISOE was the first tentative study to produce a reliable wind (onshore and offshore) atlas for the majority of the European Countries. In the Portuguese case, "Instituto Portugues do Mar e da Atmosfera" provided the wind data for the study. Several wind data from the most representative synoptic and climatological weather stations operating in the country were

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processed for a period of 10 years. It was concluded that the 10-year period was equivalent to a 30-year period, which is, from the meteorological point of view, the definition of climate (Peixoto and Oort 1992). In those days, the European Wind Atlas was considered a successful case study. Nevertheless, with the development of the wind energy sector, several drawbacks associated with the mathematical limitations of the method were identified in this Atlas. In fact, the method was not capable of describing important atmospheric phenomena for wind power purposes such as the atmospheric turbulence, stratification, and sea-land-breeze processes.

In order to improve the development of a wind atlas, several studies (Meroney and Melbourne 1991; Frank et al. 2001; Tammelin et al. 2001; Feitosa et al. 2002; Mass et al. 2002; Mortensen 2014) appeared with more robust mathematical methods to deal with local turbulence phenomena. These studies were mathematically focused over specific regional areas such as coastal, forestry areas, complex orography and landscape. It was concluded that the state-of-the-art numerical models used for weather forecast purposes are a valuable tool to produce a wind atlas with good estimates for the wind speed and wind direction. Following this line of research, LNEG started applying numerical modelling using a state-of-the-art mesoscale model, specifically MM5 (Grell et al. 1994; Skamarock et al. 2008) to produce a first preliminary wind atlas for Portugal (Costa 2004; Costa and Estanqueiro 2004; Costa et al. 2006). The results achieved from the model highlighted its adequacy to produce wind atlas at regional/national scale. These results are supported by recent work. For instance (Jimenez et al. 2007; Yim et al. 2009; Dvorak et al. 2010; Martín Mederos et al. 2011; Yamaguchi and Ishihara 2014; Hahmann et al. 2015; Waewsak et al. 2015) computed reliable climatological wind maps for heights near the most common hub height of commercial offshore wind turbines, generally at 80m height. The results of the previous work were validated using observational data mostly from buoys but also inferred from special satellites that are capable of describing the wind behaviour at sea surface.

Satellite data for offshore regions were also applied in the scope of the European FP7 project designated NORSEWInD (NORSEWInD 2007). This project was the first to use data assimilation techniques to obtain an accurate wind atlas for the Portuguese western area around Berlengas Island (Costa et al. 2010; Fernandes et al. 2010) and the Northern Seas including the Baltic Sea (Berge et al. 2009, 2012). One of the main outcomes of this project was the full validation of the final offshore wind atlas (Marujo et al. 2011). For this case, a spatial validation methodology was created to successfully validate the final offshore wind atlas for the Baltic and Northern Seas using wind satellite data and offshore meteorological weather stations (Marujo et al. 2011). The methodologies employed enabled a reliable characterization of the offshore wind in the region under analysis.

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2.2. Wave resource assessment

Wave energy has been developed by several countries since the 1970s. The first programs for the research and development of wave energy were implemented by United Kingdom, Norway, Sweden, United States and Japan. In the 1980s, the wave research strongly declined in countries such as Portugal, Ireland, India and China, but in the early 1990s there was a new interest in wave energy with the support of the European Commission (EC). The first project being funded occurred in 1992 by the European JOULE program. After this new beginning, the EC continued to support the development of this type of renewable energy source within various Framework Programs, including Horizon 2020. Programs, such as the NER300, are also important for the development of this technology since, in the last decades, this R&D activity has been expanding beyond the initial group of pioneer countries. Currently, a group of researchers from various countries has been working on the development of wave energy systems. Because of this effort, several conversion devices were built, with technologies at different stages of development, but there are still no commercial systems available.

Regarding the Portuguese case, Portugal has very favorable conditions for the development of this technology, reinforced by the technical and scientific capacity in the country to study and implement these systems and by the fact that the electricity grid near the coast is concentrated where the large consumption occurs and where the wave resource is more favorable. Portugal has been involved in R&D in this area since the early 1990s. In 1992 the JOULE program, Launched by the European Commission, was part of a European project, led by Portugal, under the Preliminary Actions in Wave R&D European Pilot Plant Study. Followed by other two projects designated by the European Wave Energy Pilot Plant on the Island of Pico, Azores, in 1993-96 and the European Wave Energy Pilot Plant on the Island of Pico, Azores, Portugal - Phase two: Equipment in 1995-98, which was also integrated into the JOULE program. These projects launched the first European experimental wave power plant in Pico Island (Azores). Over the next two decades, Portugal occupied an important position in Research and experimental development in wave energy, participating in 37 European projects (leading 13) and obtained national funding for 22 projects. Some of these projects involved the development of experimental wave energy devices on the Portuguese coast, including the testing and demonstration of the systems, e.g., the AWS and Pelamis systems.

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The first major project to assess the wave energy resource for Portugal was funded by the EC In 1994 coordinated by LNEG in which an European database for the wave energy resource in very deep waters - WERATLAS (Pontes et al. 2002) was created. Following this project, Portugal has developed other databases, *e.g.,* ONDATLAS (Pontes et al. 2005a), and PEMAP (Pontes et al. 2005b). The ONDATLAS database includes sea state and wave information for a set of 81 points in intermediate and deep waters. The PEMAP database includes information on sea depth slope, tectonic faults, ports, sea corridors, submarine cables, defense, among other spatial information data.

3. Resource assessment - Methodology

3.1. Offshore wind

In order to obtain representative local wind, or to perform a regional and/or national mapping - without direct resource to an extensive and costly network of anemometric stations - it becomes necessary to use numerical models of atmospheric forecasting, commonly called mesoscale models. These models have the ability to describe the behaviour and evolution of air masses and to treat explicitly the inherent phenomena of turbulence and atmospheric stratification. The numerical model is able to describe all the atmospheric phenomena and others with nonlinear nature, up to a maximum spatial resolution of 1x1km. Using a terrain and roughness database together with a three-dimensional set of historical meteorological data to force the boundary conditions of the model, it is possible to perform numerical physical simulations, in space and time that enable the production of a sufficiently representative statistical representation of the meteorological quantities under analysis.

The results of the numerical simulations thus obtained, can subsequently, and punctually, be compared to observed wind data from anemometric stations whose location should fit within the area limits of the simulation domain, leading to an experimental validation of the results. This way, it is possible to make adjustments/corrections to the simulations until a characteristic map of the average wind at the regional and/or national scale is obtained. In Figure 1 the methodology used by LNEG in the generation of a wind atlas with mesoscale numerical models (Costa 2004; Costa and Estanqueiro 2004; Costa et al. 2006) is represented.

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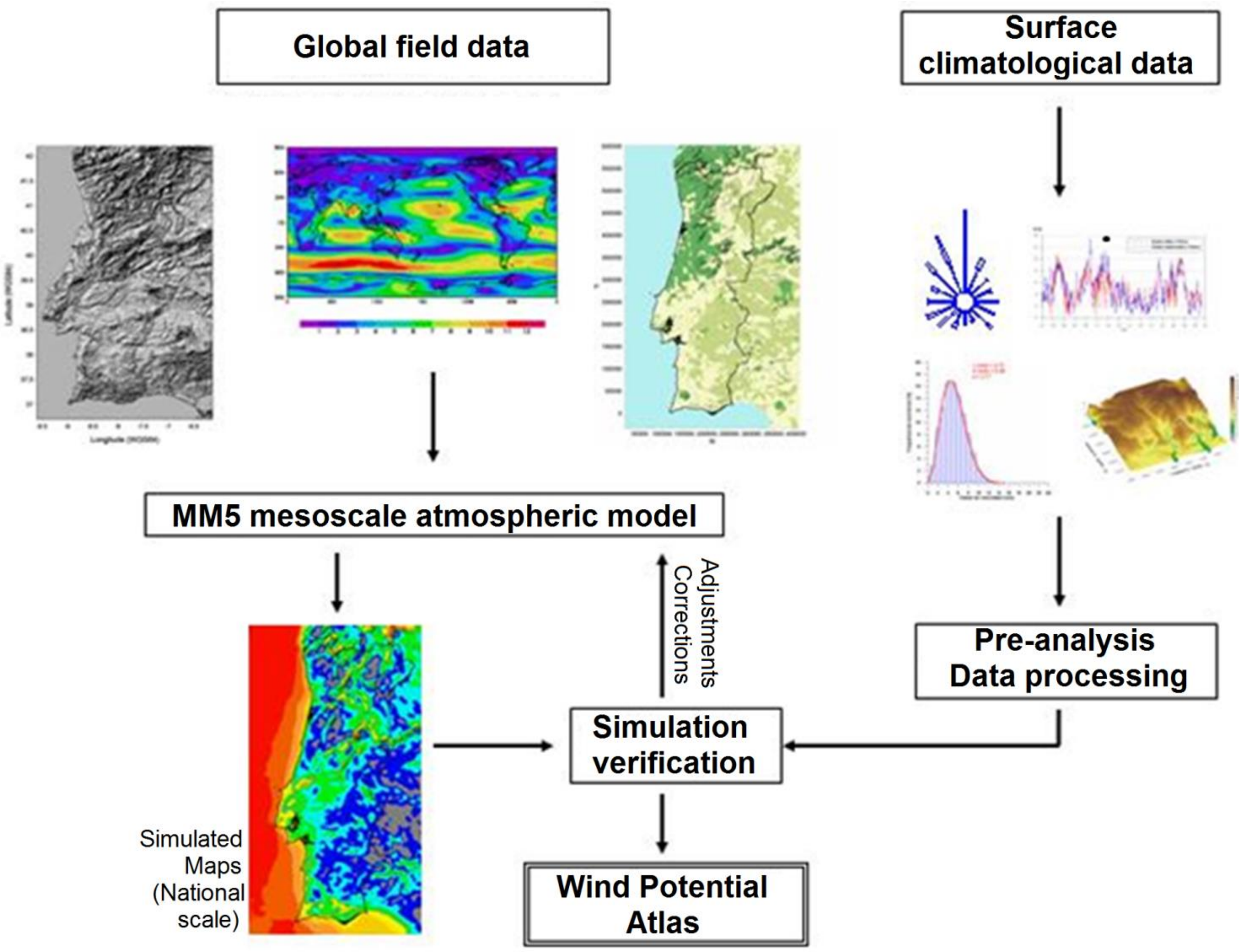

Figure 1. Methodology for the elaboration of a regional and/or national wind atlas used by LNEG. The illustration refers to the generation of the Wind Atlas and the Wind Potential for Portugal.

The previous figure depicts the overall methodology that will be employed in this project to obtain the offshore wind resource assessment (wind speed, wind direction). The proposed methodology for the offshore wind resource assessment can be split into three main steps: I.A) MM5 model calibration; I.B) Data assimilation procedures; and II) Atlas Validation. In step I.A the mesoscale model is calibrated regarding its numerical parameterizations and initial and boundary conditions. In step I.B, the benefits of the data assimilation approach to improve the wind speed estimates are tested. Step II corresponds to the second phase of this project, where offshore experimental campaigns will occur. In both steps, I.A and I.B, an offshore wind atlas will be produced and validated using the data collected during the Step II. The Atlas that shows lower deviations will be then selected. In the next subsection, a brief description of the steps I.A and I.B is presented.

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3.1.1. Mesoscale numerical model MM5

In order to obtain the offshore wind atlas for Mainland Portugal, LNEG will use the mesoscale model designated MM5 - "Fifth generation Mesoscale Model" (Grell et al. 1994) developed by PSU/NCAR - "Pennsylvania State University/National Center for Atmospheric Research", USA. Version 3.7.4, which is an atmospheric forecasting model relatively updated with physical formulation and parameterization of the atmosphere processes, and also has the advantage of being a freeware model. It is also worth mentioning that the mesoscale numerical model, MM5, is a model that has been continually improved through the collective effort of several users by universities and research institutes distributed all over the globe.

Given the complexity of the "physical packages" and parameterizations used by the numerical model, it is not the purpose of the present report to explain thoroughly its whole behaviour. Instead, a simplified description of the subprograms needed to perform any numerical simulation is presented. The model uses the vertical coordinate system "sigma" (σ) (Haltiner and Williams 1980), in which vertical coordinates follow the terrain geometry as shown in Figure 2. This vertical coordinate system has the advantage to well simulate and predict the regional or local atmospheric circulation physics.

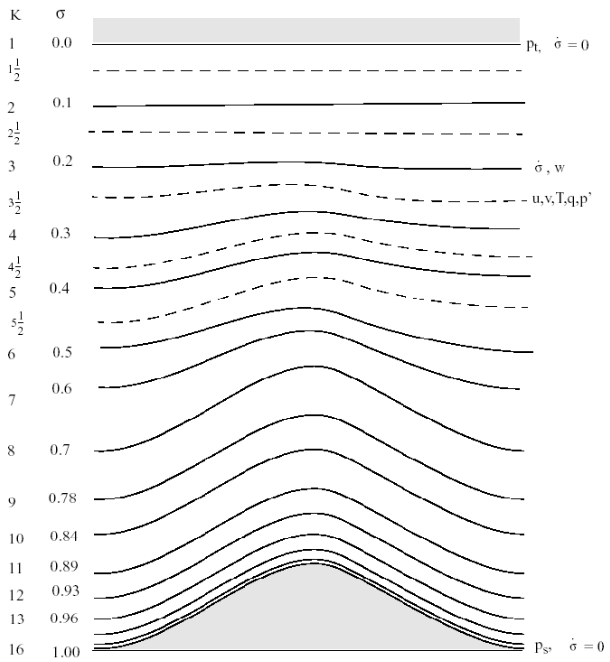

Figure 2. Schematic representation of the vertical coordinate system "sigma" (σ). In this figure, 16 vertical levels are depicted (Grell et al. 1994).

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The MM5 model is composed by a set of executable and independent modules. The set of information processed by each module constitutes the main input information to run the main program, which is also referred as "MM5". Numerical simulations are performed through the main program - "MM5" which provides the forecasts of the meteorological fields based on a set of numerical parameterization. Based on observational data, the different numerical parametrizations available in the MM5 model will be tested to identify the most appropriate for the region under analysis. The independent modules required to perform a MM5 simulation are; TERRAIN, REGRID, INTERPF and NESTDOWN. Figure 3 depicts the modules needed in their execution order during a MM5 simulation.

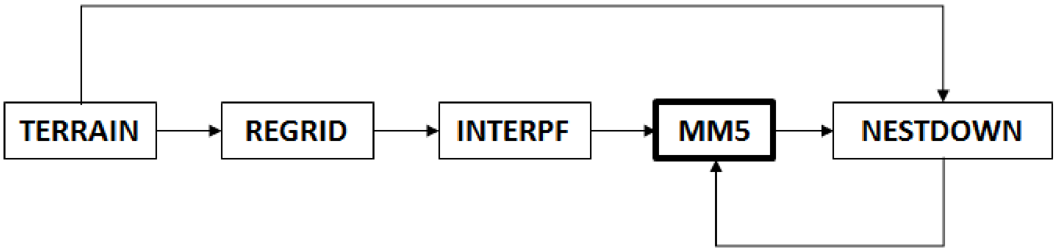

Figure 3. Schematic representation of MM5 modules during an MM5 model simulation (Grell et al. 1994).

The TERRAIN module defines the geometry of the domain area and nested domain areas. For each generated domain or nested domain, the module processes the orography and roughness data into a convenient map projection system used by the model. In this module is also defined the domain spatial resolution and the refined spatial resolution for each nested domain.

The REGRID module processes the three-dimensional and two-dimensional historical meteorological data, known as reanalysis and performs interpolation procedures to adapt the reanalysis data to model domain geometry. The output from the interpolation procedures is usually known as the “first guess" atmospheric data to be ingested into the numerical model.

The INTERPF module ingests the results from REGRID and performs a vertical interpolation of the meteorological data to a "sigma" vertical coordinate system used by the MM5 model. It should be noted that the vertical resolution of the model is defined based on the number of sigma levels. The execution of the INTERPF module also generates the initial and boundary conditions for the execution of the MM5 model.

The NESTDOWN module is capable of generating new boundary and initial condition fields based on a previous MM5 model coarse domain. The NESTDOWN module is run when nested domains are present. In this case, the

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generated boundary and initial conditions fields for the nested domain contain more spatial atmospheric variability structures when compared with reanalysis database.

3.1.2. Orography and roughness information

The orography, vegetation cover and dominant soil type's information needs to be included in the model in order to characterize the wind flow behaviour near the sea/land cross-border. The topography database used for each domain or nested domain is provided by the GTOPO30 database - "Global 30 arc-second TOPOgraphic data" developed by the USGS - "United States Geological Survey" (USGS 2004a). The orography of this project has a spatial resolution of approximately 1x1km and presents itself as a high quality topographic database.

Regarding vegetation cover and dominant soil type, a database from the USGS Land Cover Project (USGS 2004b) is used. It classifies the soil and vegetation cover in 24 different classes, such as forest, water, etc., with a spatial resolution of 1x1km. This high-quality database will be processed for the model domain and nested domains.

3.1.3. Boundary and Initial Conditions

One of the main sources of error and uncertainty in the wind resource assessment, when numerical mesoscale models are applied, is derived from the initial and boundary conditions (IBC) that fed the model, which are essentially atmospheric information provided by reanalysis and/or analysis products (Parker 2016). Indeed, several authors show that these data have a crucial impact on the outcomes of the mesoscale model (Wang and Zeng 2012; Alvarez et al. 2014; Carvalho et al. 2014a, b, c; Soukissian and Papadopoulos 2015). Therefore, whenever the meteorological measured data are available, sensitivity tests need to be performed to select the most suitable IBC product to feed the mesoscale model in that region. In this sense, within the scope of this project, this procedure will also be performed.

The first generation of reanalyses comprised three datasets: the NCEP-R1 (NCEP/NCAR 1994) produced and released by National Centre for Environmental Prediction (NCEP), the ERA-40 (Berrisford et al. 2011) produced and released by European Centre for Medium-Range Weather Forecasts (ECMWF) and the JRA-25 (Gelaro et al. 2017) produced and released by Japanese Meteorological Agency. Later, the NCEP-R1 was improved by fixing some errors and by updating the model parametrizations. As a result, a new product NCEP-R2 (NCEP/DOE 2000) was released. This procedure also occurred for the remaining datasets. Nowadays, among reanalysis datasets the most widely used are the following: the NCEP-R2, the NCEP Climate Forecast System Version 2

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(NCEP-CFSv2) (Saha et al. 2011), the ECMWF ERA-Interim (Berrisford et al. 2011) and the NASA Modern-Era Retrospective Analysis for Research and Applications Version 2 (NASA MERRA-2) (Gelaro et al. 2017). Currently, the analysis datasets namely, the NCEP Global Forecast System (NCEP-GFS) (National Centers for Environmental Prediction NOAA, U.S. Department of Commerce 2015) and the NCEP Final Analysis (NCEP-FNL) (National Centers for Environmental Prediction NOAA 2000) also show a good performance regarding the wind speed and direction characterization being widely used in wind power sector.

In addition to their own parametrizations, the key difference between the reanalyses and analyses products aforementioned are related to the: a) amount of observational data assimilated as well as the type of observational atmospheric equipment's used; b) data assimilation system; and c) spatial horizontal and vertical resolution. Based on the aforementioned literature in Table 1, a comparison of the different analysis and reanalysis datasets is provided.

Table 1. Main characteristics of the several reanalyses and analyses used to feed MM5 mesoscale model [Adapted from: (Carvalho et al. 2014a)].

Dataset	Type of dataset	Assimilation system	Horizontal res. (Lat. X Lon.)	Vertical levels	Temporal coverage
NCEP-R2	Reanalysis	3D-Var	2.50° x 2.50°	28	1979–Present
NCEP-CFSv2	Reanalysis	3D-Var	0.50° x 0.50°	64	2011–Present
ERA-Interim	Reanalysis	4D-Var	0.75° x 0.75°	60	1979–Present
NASA-MERRA-2	Reanalysis	3D-Var	0.50º x 0.63º	72	1980–Present
NCEP-GFS	Analysis	3D-Var	0.25° x 0.25°	64	2015–Present
NCEP-FNL	Analysis	3D-Var	1.00° x 1.00°	52	1999–Present

It should be highlighted that, the results in literature (Wang and Zeng 2012; Alvarez et al. 2014; Carvalho et al. 2014a, c; Sharp et al. 2015; Santos et al. 2017) show that it is not completely clear which reanalysis or analysis product is the best since they present quite similar results and often the best product changes from one site to another. Therefore, a sensitivity test of each reanalysis/analysis product for the region under study is always recommended.

In this project, using the common statistics metrics (*e.g.*, the normalized mean square error and the Pearson correlation) and observational data, the different reanalysis/analysis presented in Table 1 will be tested to identify the most suitable IBC data to feed the model. The observed meteorological data are collected from different

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measurements systems, namely, oceanographic buoys near the Portuguese coast (Raia, Monican01, Monican02, Cabo Silleiro and Golf de Cádiz) provided by the Portuguese Hydrographic Institute (Instituto Hidrográfico 2017) and Spanish Puertos del Estado agency (Puertos del Estado 2017), coastal anemometric masts, ZephIR instruments – vertical and horizontal wind profiler – as well as sea surface wind inferred by satellites.

A first offshore wind resource assessment will be performed, based on the most appropriate numerical model parameterizations and IBC. All the aforementioned procedures correspond to the step I.A.

3.1.4. Data Assimilation

The concept of data assimilation consists of an advanced technique by which observations are combined with a "first guest" or "background forecast" product derived from a numerical weather prediction model (NWP) (Daley 1993). The combination of observations and the model give a reliable representation of the "true" state of the atmosphere or the "analysis" at a defined time. Below some details regarding the data assimilation procedures – Step I.B – are provided.

A) Data assimilation techniques

There are three different types of data assimilation techniques. The 3DVAR (Barker et al. 2004, 2012), the 4DVAR (Huang et al. 2009) and the 4FDDA (Hoke and Anthes 1976; Kuo and Guo 1989; Stauffer and Seaman 1990) concepts. The 3DVAR or 3D variational technique consists of an iterative minimization procedure able to minimize errors between the local observations and the "first guest" or "background forecast" product. The 4DVAR or 4D variational technique is a more complex method but still similar to 3DVAR. The main difference relies on the error minimization methodology. Commonly, the minimization is performed using a time window period where different observations at different times are available to build a "best-fitted" state of the atmosphere. This "best-fitted" state is indeed the "analysis" outcome from 4DVAR.

In fact, not every type of observation can be assimilated by 3DVAR or 4DVAR methods. One example of this type of observations are the ones available at high frequency rates such as 10min interval (Kuo and Guo 1989). Generally, observations with high frequency rates are used for wind power studies since they enable to describe the stratification and turbulence effects, which have a crucial impact in the wind resource characterization. For this time resolution, another type of data assimilation scheme should be used, namely the observational FDDA (four-dimensional data assimilation) technique. The observational FDDA scheme can deal with high frequency observational assimilation with a low computational cost. The scheme basically adapts the model's dynamic

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balance to adapt the mass field variables and thus correct and reduce errors from the mass fields such as the wind speed (Kuo and Guo 1989; Stauffer and Seaman 1990).

The observational FDDA technique is promising for using observations with high frequency and particularly to the wind field, which is an important variable to be studied and simulated for wind resource assessment. For the new Portuguese wind atlas development, it is pretended to use the observational FDDA data assimilation scheme. The scheme enables to assimilate observational high frequency wind data (10min. resolution interval) gathered from previous experimental campaigns in the west coastal areas of Continental Portugal, which includes the anemometric masts, buoys and wind data inferred by vertical wind profiles describing the wind speed behaviour at different heights (surface to 300m height).

B) The observational FDDA data assimilation scheme

The observational FDDA data assimilation scheme is a purely mathematical procedure coupled to model equations according to equation 1 (Kuo and Guo 1989; Stauffer and Seaman 1990);

$$\frac{\partial \alpha}{\partial t} = F + G\frac{\sum_{n=1}^{N} W_n^2 \Delta\alpha}{\sum_{n=1}^{N} W_n} \qquad (1)$$

where $\frac{\partial \alpha}{\partial t}$ is the model predictive equation, F includes the advective and forcing terms normally used in the model such as the model parameterizations, G the so-called nudging coefficient, N is the total number of observations to be assimilated and W_n a weighting coefficient that controls how the influence of an observation varies in time and horizontal distance – spatial correlation. The term $\Delta\alpha = (\alpha_{obs}^n - \alpha_{model})$ with α_{obs}^n defined as the n*th* observation of the variable α and α_{model} defined as the model predicted value of the variable α interpolated to the observation position. The weighting coefficient varies in time and space according to equation 2;

$$W_n = W_n^t \, W_n^{xyz} \qquad (2)$$

with the time variations described using W_n^t according to equation 3;

$$W_n^t = \begin{cases} 1.0, & |t_{obs}^n - t_{model}| \leq T/2 \\ \dfrac{2(T - |t_{obs}^n - t_{model}|)}{T}, & \dfrac{T}{2} < |t_{obs}^n - t_{model}| < T \\ 0.0, & |t_{obs}^n - t_{model}| \geq T \end{cases} \qquad (3)$$

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where T is the half-period for a predetermined time window over which an observation will influence the model simulation, t_{obs}^{n} is the nth observation time and t_{model} is the model time under simulation. The weighting coefficient also varies in a horizontal and vertical distance according to equation 4;

$$W_n^{xyz} = \begin{cases} \dfrac{R^2 - \left(r_n^{xyz}\right)^2}{R^2 + \left(r_n^{xyz}\right)^2}, & r_n^{xyz} < R \\ 0.0\,, & r_n^{xyz} \geq R \end{cases} \quad (4)$$

where, R is a predefined radius of influence or distance correlated influence and r_n^{xyz} the distance between the model grid point and the observation. Figure 4 depicts the flowchart of the observational FDDA technique under working. Figure 5 and Figure 6 illustrate the weighting coefficients variations in time and space during FDDA running.

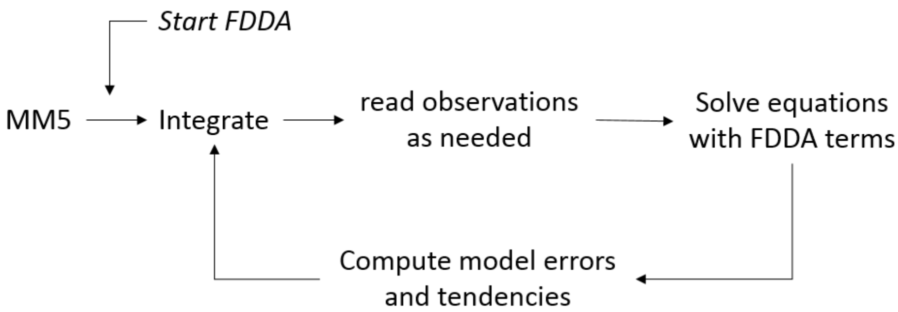

Figure 4. Flowchart of the observational FDDA assimilation system run.

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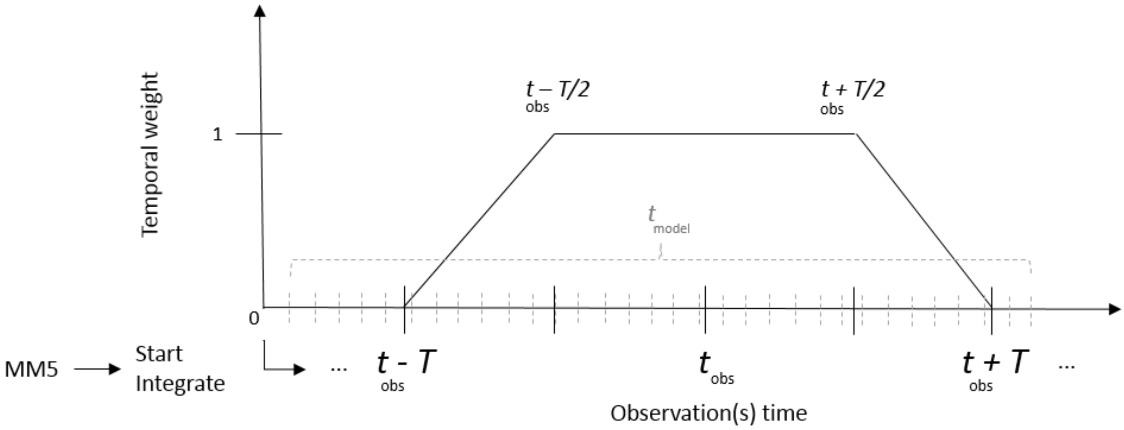

Figure 5. Temporal weighting function for observation(s) influences during model integration over the time window *T*.

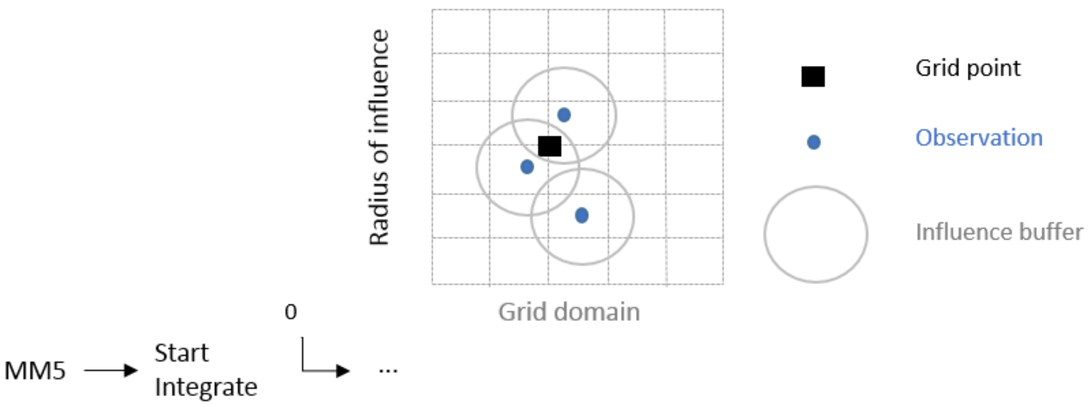

Figure 6. Spatial weighting function – radius of influence of observation(s) around model grid points.

The observational FDDA scheme depends on parameters G, T and R whose values must be pre-established. For the case of R – the radius of influence, it will be used the value of 100km which is a common typical value for mesoscale domain simulations (Kuo and Guo 1989). The parameter T, which represents the half time window used for assimilating observations, must take into account the time discretization from the available observations. The parameter G must be chosen according to the minimization of mass balance errors between model forecast and observations. There is no general way to fix the previous parameter, and the common procedure is based on sensitivity analysis using observational data. The most relevant studies (Hoke and Anthes 1976; Kuo and Guo 1989; Stauffer and Seaman 1990) to find the most appropriate G value have been conducted for mesoscale simulation with spatial resolutions ranging from 1km to 5km. The results from previous authors show that the most accurate results using high frequency observations, regardless latitude or longitude, were achieved for a G value

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of 3×10^{-4}. Therefore, for the development of the new wind atlas for Continental Portugal, this value will be used in the data assimilation simulations.

C) Databases used for the observations FDDA data assimilation scheme.

Currently, some wind products derived from satellite-observation can already provide accurate meteorological data (Penabad et al. 2008; Alvarez et al. 2014; Balog et al. 2016; Santos et al. 2017), which can be assimilated in the mesoscale models (Lorenz and Barstad 2013; Peng et al. 2013). Thus, one of those products, available from 2012-11-15 to present, is the Blended Mean Wind Field estimated from scatterometers ASCAT and OSCAT retrievals and ECMWF operational wind analysis with a horizontal resolution of 0.25x0.25 degrees and temporal resolution of 6 hours (Bentamy and Croize-Fillon 2012; Bentamy 2016). Another one, available from December 2012-12-23 to present, is the Global Ocean daily L3 gridded sea surface wind observations from ASCAT on MetOp-A and MetOp-B with a horizontal resolution of 0.125x0.15 degrees (Tilly Driesenaar, Jos de Kloe, Ad Stoffelen 2017). Regarding the observed meteorological data, part of the datasets already described in section 3.1.1 will be used exclusively in the data assimilation. Table 2 lists the meteorological databases and meteorological parameters expected to be used during the observational FDDA data assimilation run.

D) The observational FDDA data assimilation runs

The observational FDDA data assimilation will be run, firstly, as a cross-validation case. A temporal extension of 3 months will be used for this scenario case study. The cross-validation run case scenario has an objective: test if FDDA approach improves (or not) the model wind speed and direction forecasts. In this sense, the forecasted estimates are compared with independent wind observations and some statistics will be produced. If a database or databases show significant statistic deviations, then it will be discarded (dumped) for the second run case. Otherwise, the second run will be the official run to simulate the new wind atlas for Mainland Portugal.

Table 2. Meteorological databases and parameters used for the observational FDDA run.

Meteorological database	Meteorological parameter to assimilate	Temporal Resolution
ASCAT database (satellite)	Wind at sea surface	12 hours
Buoys (marine)	Wind, pressure at sea surface	1 hour
Synoptic coastal stations	Wind, temperature, humidity, surface pressure at 10m height and sea level pressure	3 hour

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Synoptic soundings at Lisbon and Lajes (Azores island)	Wind, temperature, humidity and pressure at several vertical levels – the mandatory levels	3 hour
Coastal Anemometric masts	Wind at some levels (e.g. 10m, 40m, 60m 80m) according sensors availability	10 min
WindFloat LiDAR	Wind at some levels (e.g. 40m, 60m, 80m, 100m and 120m) according data quality	10 min

3.2. Wave and sea state assessment

To perform wave resource assessment it is necessary to obtain sea surface elevation data. Data can be obtained from numerical modelling or from experimental observations such as directional or non-directional boys – see Figure 7; pressure transducers - see Figure 8; synthetic aperture radar data (satellite) – see Figure 9; and resistive or capacity transducers – see Figure 10.

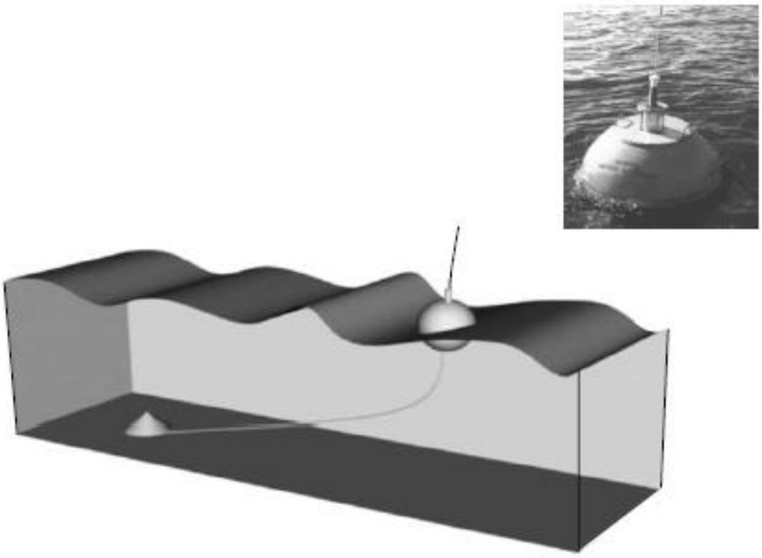

Figure 7- WaveRider buoy type to measure the sea surface elevation. (Holthuijsen 2007)

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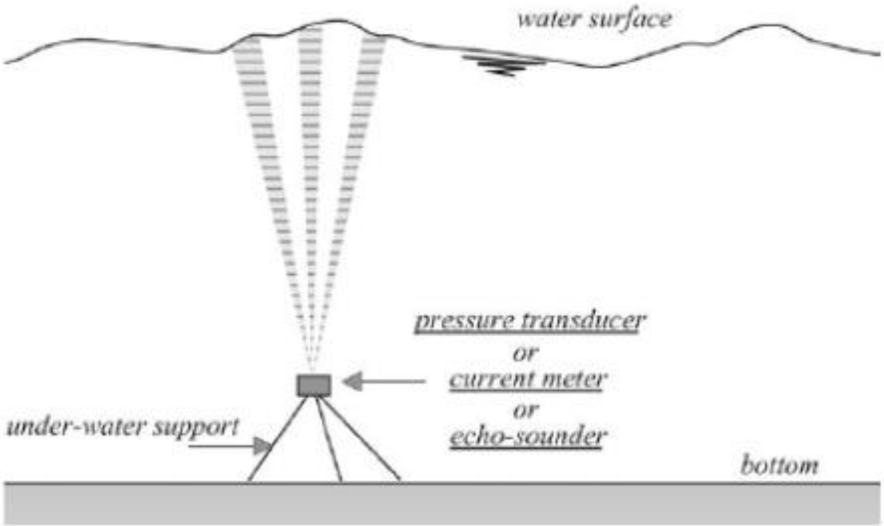

Figure 8 - Pressure transducer to measure sea surface elevation. (Holthuijsen 2007)

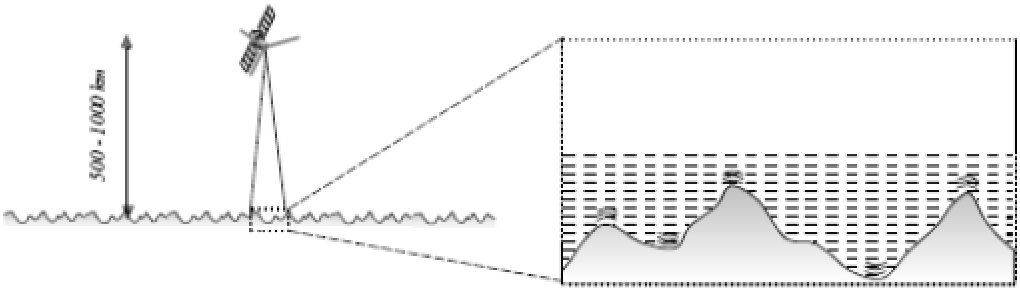

Figure 9 - Synthetic apperture radar satellite. Measures and estimates the sea surface elevation and surface wave parameters. (Holthuijsen 2007)

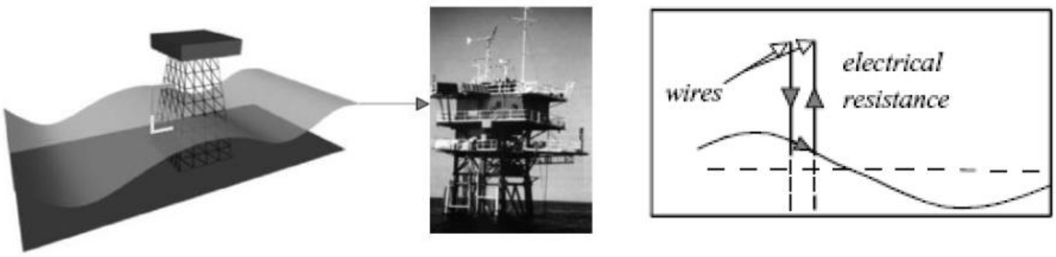

Figure 10 - Capacity or resistivity transducers to measure the sea surface elevation. (Holthuijsen 2007)

Numerical modelling shall be applied for the area of interest over which a mesh is created. Initial and boundary condition data, as well as bathymetry are required to run the model. The output from the numerical modelling is mainly directional wave spectra S (f, θ) for each grid cell point.

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Buoys measure the sea surface elevation by accelerometer instruments – see Figure 11. Using specific software it is possible to compute directional or not directional wave spectra $S(f)$.

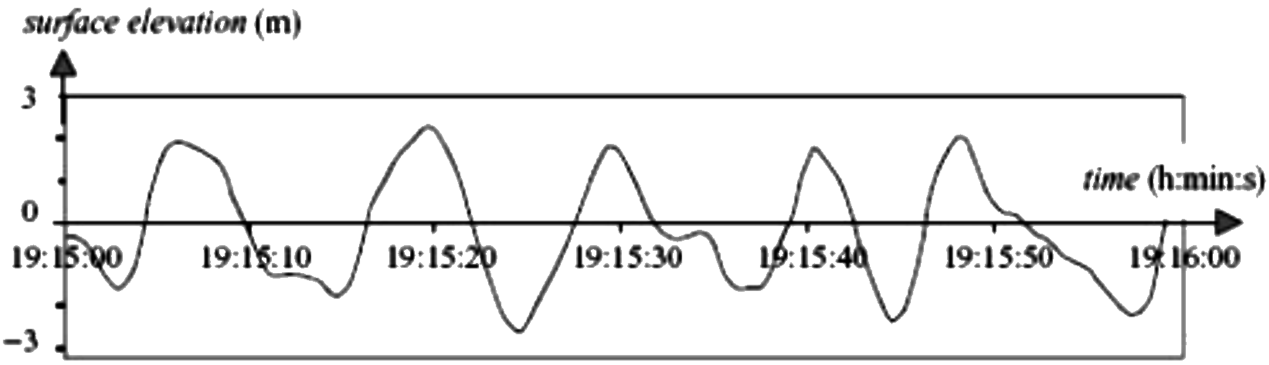

Figure 11 - Surface elevation recorded data from a WaveRider buoy type. (Holthuijsen 2007)

Once wave spectra is computed it is possible to derive other sea surface and wave parameters such as the significant sea surface height, wave peak period, power (or energy flux) from the waves, the wave group directional as well as other parameters. Based on the obtained parameters that can be computed for several time instances in several years of ranging, it is possible to compute the mean wave behavior. Such statistics define the wave resource assessment atlas for the regions under study. Table 3 illustrates for each observational data source which parameter can be computed.

Table 3 - Observational data source and associated wave parameters that can be computed. . $\boldsymbol{S(f) = E(f)}$- non directional wave spectra, $\boldsymbol{\overline{\theta}(f)}$ – mean wave group direction per frequency, $\boldsymbol{\sigma_\theta}$ – standard deviation for the wave groupd direction per frequency, $\boldsymbol{H_s}$ – significant wave height, $\boldsymbol{T_e}$ – energy period, $\boldsymbol{T_p}$ – wave peak period, $\boldsymbol{T_z}$ – cross zero wave period, $S(f, \theta)$ – directional wave spectra.

Data Source	Device/Model		Data Type
Measurements	In-situ	Buoys	$E(f), \theta(f), \sigma_\theta(f)$
		Pressure, laser, acoustic probes	$H_s(\&T_e, T_p)$
	Remote sensed	Satellite altimeter	$H_s(T_Z - \text{mod } el)$
		Satellite (A)SAR	$S(f, \theta)$
		Ground-based Radar	$S(f, \theta)$
Wind-wave models	3rd generation models (WAM, WaveWatch III and other models), and also UK Met Office model (2nd generation)		$S(f, \theta)$

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A) Wave parameters

The local behavior of the waves can be described through the sea state wave spectra *S (f, θ)*, which specifies the wave energy. This wave energy is proportional to the sea surface elevation variation in terms of frequency *f* and directionθ . The wave spectra can be obtained by the significant wave height H_s and the wave peak period T_p. Both obtained by direction.

The frequency spectra which describes the wave energy in the frequency domain is related with the directional spectra as:

$$S(f) = \int_0^{2\pi} S(f,\theta)d\theta \qquad (5)$$

where f is the frequency and θ the direction of the incident waves

To compute the wave parameters based on spectra information S (f, θ) e S (f) it's necessary to use statistical spectral momenta defined as:

$$m_n = \int_0^{\infty} f^n S(f)df \qquad (6)$$

or

$$m_n = \int_0^{\infty}\int_0^{2\pi} S(f,\theta)d\theta df \qquad (7)$$

Some of wave and energy parameters can be calculated as:

$$H_s \approx 4\sqrt{m_0} \qquad (8)$$

where H_S is the significant wave height

$$T_p = \frac{1}{f_p} \qquad (9)$$

where f_p the frequency wave peak period and T_p the wave peak period

$$T_e = \frac{m_{-1}}{m_0} \qquad (10)$$

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where T_e the wave energy period.

The energy flux or power level per length unit of the wave crest is given by

$$P = \rho g \int_0^\infty c_g(f,h)S(f)\,df \tag{11}$$

or to a directional spectrum:

$$P = \rho g \int_0^\infty \int_0^{2\pi} c_g(f,\theta,h)S(f,\theta)\,d\theta df \tag{12}$$

where ρ is the sea water density, *h* local depth and *g* gravity acceleration.

In what concerns the wave direction, the mean wave direction is given by:

$$\bar{\theta}_w = arctang \frac{\int_0^\infty \int_0^{2\pi} S(f,\theta)\sin(\theta)d\theta df}{\int_0^\infty \int_0^{2\pi} S(f,\theta)\cos(\theta)d\theta df} \tag{13}$$

and the mean power direction is given by:

$$\bar{\theta}_P = arctang \frac{\int_0^\infty \int_0^{2\pi} S(f,\theta)\mathrm{cg}(f,\theta,h)\sin(\theta)d\theta df}{\int_0^\infty \int_0^{2\pi} S(f,\theta)\mathrm{cg}(f,\theta,h)\cos(\theta)d\theta df} \tag{14}$$

When the directional data are obtained from mean wind direction per frequency band, θ_b, and $S(f)$, it is:

$$\bar{\theta}_w = arctang \frac{\int_0^\infty S(f)sin(\theta_b)df}{\int_0^\infty S(f)cos(\theta_b)df} \tag{15}$$

$$\bar{\theta}_w = arctang \frac{\int_0^\infty S(f)cg(f,h)sin(\theta_b)df}{\int_0^\infty S(f)\,cg(f,h)cos(\theta_b)df} \tag{16}$$

B) <u>Wave data statistics</u>

The statistics that represent the climate sea wave state are the mean values obtained from the parameters H_S, T_p, T_e and *P* and direction $\overline{\theta_w}$ e $\overline{\theta_P}$ and the bivariate statistics (dispersion diagrams) (H_S, T_P), (H_S, T_e) and $(H_S, \bar{\theta}_w)$. Sometimes, histograms for H_S; T_e and T_p; *P* and θ_b are also obtained. As an example, two dispersion diagram types, Figure 12 and Figure 13 based on (H_S, T_P) and (H_S, T_e) respectively are presented.

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Significant height (m)

One-way peak period (s) — ‰ / m / s	< 0,5	0,5 - 1	1 - 1,5	1,5 - 2	2 - 2,5	2,5 - 3	3 - 3,5	3,5 - 4	4 - 4,5	4,5 - 5	5 - 6	6 - 7	7 - 8	8 - 9	9 - 10	10 - 12	12 - 14	14 - 16	16 - 18
3 - 4																			
4 - 5																			
5 - 6	0.5	4.2	0.7																
6 - 7	1.4	58.3	20.8	0.5															
7 - 8	1.2	**127.7**	83.4	7.5	1.4	0.1													
8 - 9	0.5	94.2	121.7	25.0	4.2	1.8	0.3												
9 - 10		51.2	108.7	46.0	13.7	6.4	1.4												
10 - 11		29.3	83.2	59.4	29.2	12.5	3.6	1.5											
11 - 12		21.8	64.7	55.2	34.9	19.7	9.0	3.8	1.4	0.1									
12 - 13		15.1	53.0	58.7	36.8	23.8	13.8	6.2	3.3	1.2	0.1								
13 - 14		6.2	33.0	47.4	43.0	25.6	14.4	5.9	4.9	2.2	0.5	0.1							
14 - 15		2.7	17.2	31.2	33.4	24.4	17.0	9.3	7.4	4.4	1.1	0.3	0.1						
15 - 16		1.9	10.7	16.8	21.2	14.9	14.1	10.5	9.4	5.2	3.2	0.5							
16 - 17		0.4	3.1	7.5	9.3	7.5	8.8	8.9	10.3	4.7	2.8	0.9	0.2	0.1					
17 - 18		0.4	1.8	4.0	2.9	4.7	3.8	4.5	4.0	3.3	2.3	1.5	0.6	0.2					
18 - 19			0.7	0.8	0.5	1.9	2.1	1.6	2.6	0.7	0.5	0.4	0.3	0.4					
19 - 20			0.3	0.7	0.3	0.3	0.4	0.5	0.4	0.1	0.5	0.3	0.4	0.3	0.2				
20 - 21						0.1	0.1	0.1	0.3		0.2		0.1						
21 - 22					0.1						0.2			0.2					

Figure 12 - Dispersion diagram $(\boldsymbol{H_S}, \boldsymbol{T_P})$. *Per thousand* of the year in which a given cell occurs (sea state). Local 41º22,3`N, 8º46,9`W.

Significant height (m)

Energy period (s) — ‰ / m / s	< 0,5	0,5 - 1	1 - 1,5	1,5 - 2	2 - 2,5	2,5 - 3	3 - 3,5	3,5 - 4	4 - 4,5	4,5 - 5	5 - 6	6 - 7	7 - 8	8 - 9	9 - 10	10 - 12	12 - 14	14 - 16	16 - 18
3 - 4																			
4 - 5	0.7	8.2	1.8																
5 - 6	2.7	158.6	83.5	5.1	0.1														
6 - 7	0.3	161.5	**180.4**	37.8	6.6	1.9													
7 - 8		57.1	159.0	80.9	31.6	13.4	3.1	0.3											
8 - 9		24.6	106.5	89.0	51.5	29.4	13.0	5.1	0.8										
9 - 10		2.6	55.6	84.3	51.9	33.0	18.2	8.5	7.0	1.8	0.1								
10 - 11		0.7	12.6	47.4	50.8	34.5	23.1	11.8	9.4	5.6	1.4	0.1							
11 - 12			2.6	12.7	31.1	20.9	19.2	13.8	11.9	7.5	3.6	0.3	0.1						
12 - 13			1.0	3.6	6.3	7.3	9.0	8.2	8.5	4.1	3.6	1.8	0.1						
13 - 14				0.1	1.0	3.3	2.7	4.7	4.5	2.1	1.7	1.0	0.7	0.3					
14 - 15					0.1		0.3	0.5	1.5	0.7	0.6	0.5	0.5	0.7	0.1				
15 - 16								0.1	0.3	0.1	0.4	0.2	0.3	0.1	0.1				
16 - 17														0.1					
17 - 18																			
18 - 19																			
19 - 20																			
20 - 21																			
21 - 22																			

Figure 13 - Dispersion diagram$(\boldsymbol{H_S}, \boldsymbol{T_e})$. *Per thousand* of the year in which a given cell occurs (sea state). Local 41º22,3`N, 8º46,9`W

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4. Final Notes

The main objective of this deliverable was to describe the offshore wind and wave resource assessment methodologies.

Given the impracticality of studying the Portuguese offshore wind potential using the experimental data, the only viable way is through numerical simulations. To overcome uncertainty associated with the use of these models, LNEG will resort to data gathered (in previous projects, public meteorological nearshore stations, buoys, etc.) to perform sensitivity tests to calibrate the MM5 model (Step I.A) and also to a data assimilation approach (Step I.B). Moreover, the results will be validated through data collected in several strategic points of the Portuguese coast (Step II). For the project POSEUR, a very high resolution offshore wind atlas for the Portuguese coast, with 1x1km spatial resolution comprising the continental Portuguese shore up to a bathymetric depth of about 300m, will be produced. The spatial resolution is adequate to describe the wind phenomena over the sea and in the cross-border sea/land areas. The obtained offshore wind atlas will refine much more the identification of adequate areas for offshore wind park deployment and thus improve the spatial planning of marine energy sources for the maritime area of Continental Portugal. The results will be presented in the form of a wind atlas. This atlas will be generated by calculating the mean wind speed and direction values for each cell of the 1x1km grid domain for common offshore wind turbine hub heights. Then, the results will be represented in a map form, displaying both, the wind intensity and wind direction and processed to a format compatible with the most common geographic information system software to enable the application of spatial planning methodologies.

The wave resource assessment will be based on computation of statistical parameters that describe the wave and sea surface behaviour. The data used to develop the wave resource will be based on two databases namely the WERATLAS and ONDATLAS. For the cases where both databases contain no data at a particular region, then it will be filled by numerical modelling estimation using the MAR3G model. It is also expected to be used observational data provided by the Instituto Hidrográfico buoys that operate along the coastal regions of Portugal. Having the statistical parameters computed the spatial maps can be obtained and will be processed into a Geographical System Information compatible format. Then the database PEMAP will be used to cross the wave resource with sea restrictions. Therefore, it is possible to obtain the most adequate zones to deploy wave energy devices.

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