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Wind height distribution influence on offshore wind farm feasibility study

Guido Benassai [a]* , Renata Della Morte [a], Antonio Matarazzo [b] Luca Cozzolino [a]

[a] *University of Naples Parthenope, Engineering Dept, Centro Direzionale Isola C4, 80143 Naples, Italy*
[b] *Graduate Student, University of Naples Parthenope, Engineering Dept, Centro Direzionale Isola C4, 80143 Naples, Italy*

Abstract

In this paper the Monin-Obukhov theory, with the modifications induced by the Charnock model, is used for the description of the wind speed profile and its implications on the potential site productivity of an offshore wind farm. The estimated gross annual energy production has been obtained starting from field wind data measured at 10m height, and the different theories have been used to derive the wind data at 85 m height. The comparison of the different annual directional distribution of the wind speed has been made, and the relative implications on the power production of an offshore wind farm have been discussed.

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1. Introduction

The economic feasibility of offshore wind power utilization depends on the favourable wind conditions offshore as compared to sites on land. The higher wind speeds have to compensate the additional cost of offshore developments. However, not only the mean wind speed is different, but the whole flow regime, as can be seen in the vertical wind speed profile. The commonly used models to describe this profile have been developed mainly for land sites, so they have to be verified on the basis of field data. Monin-Obukhov theory [1] is used for the description of the wind speed profile. From a given wind speed at one height, the profile is predicted using the two parameters,

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* Corresponding author. Tel.: +39-081-5476590; fax: +39-081-5476646.
E-mail address: benassai@uniparthenope.it

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namely the Monin-Obukhov length and sea surface roughness. However, the roughness is not constant with wind speed like for land surfaces, but depends on the wave field present, which in turn depends on wind speed, upstream fetch (distance to coast), water depth, etc. Different models have been proposed to describe these dependencies, among which the most commonly used is the Charnock model [2], which only depends on friction velocity. Numerous attempts have been made to improve this description by including more information about the wave field, e.g. by including wave age [3] or wave steepness [4] as additional parameters. These additional parameters require wave measurements, which are often not available for wind power applications. A fetch dependent model has therefore been developed, where the wave age has been replaced using an empirical relation between wave age and fetch [5].

In this paper the Monin-Obukhov theory, with the modifications induced by the Charnock model, is used for the description of the wind speed profile and its implications on the potential site productivity of an offshore wind farm. This physical effect has been discussed in view of a feasibility study of an offshore wind farm site in Southern Italy. After the description of the data and the methods used for the evaluation of the vertical structure of the wind velocity, a comparison between the Monin-Obhukov theory and its modification with the Charnock model has been made, in order to evidence its implications on the annual energy production.

2. Wind data

Available data consisted of time histories of wind speeds and directions collected by National Tidegauge Network (Rete Mareografica Nazionale) at the height of 10m a.s.l. in ports. The wind velocity, air and sea temperature in the sites of Bari, Vieste and Ancona have been examined, here only the Bari results will be given, for the sake of brevity.

The time series analyzed consists of the wind records acquired during the period 01/01/2010 - 31/12/2013 in the ISPRA meteo-oceanographic station located inside the Bari harbor (fig. 1a). As table 1 shows, the station has an excellent performance with a percentage of missing data virtually negligible. Only in the year 2013, the percentage of missing measures comes to 9,20%, which however can be considered acceptable.

Table 1. Wind data recorded at Bari Ispra station – expected and missing data

Year	Expected data	Missing data (%)
2010	8760	1,32
2011	8760	0,50
2012	8784	2,69
2013	8760	9,20

Fig. 1b shows the annual wind rose, based on the measurements at the standard height of 10 m a.s.l. The wind measurements at the standard 10m height show that the largest number of observations come from 270 °N, which occurrence rate is of 7,91%, and those from 210° N, which occurrence is 7,66%.

Generally speaking, the winds from 270°N and from 285° North, are coming from land and mostly belong to the classes of speeds ranging between 6 and 12 m/s, only a small percentage belong to the higher speed class of 12m/s. The latter mainly blow from the sea (northwestern winds), and are found mainly in winter. The winds of speed class 6 to 12 m/s, as pointed out before, coming from the directions ranging from 255° to 330° N, are present throughout the year and occur with higher frequency in the winter season. The winds from 210° N, belong to the speed class between 2 and 4 m/s, they are present in almost equal measure in all seasons.

The analysis of wind data related to 10m height shows that the prevailing winds (i.e. those belonging to the classes of higher speeds) blow from the NW (Mistral). With regard to the winds that have the highest frequency of appearance, which however remains less than 50%, these are predominantly westerly wind. These considerations may be useful for the orientation of the wind turbines in the site of interest.

The aforementioned frequencies for the higher winds will be increased by the transformation of wind speed at the nacelle altitude of 85 m, estimated by the theory of Monin-Obhukov, modified to take into account the lower roughness of the sea surface.

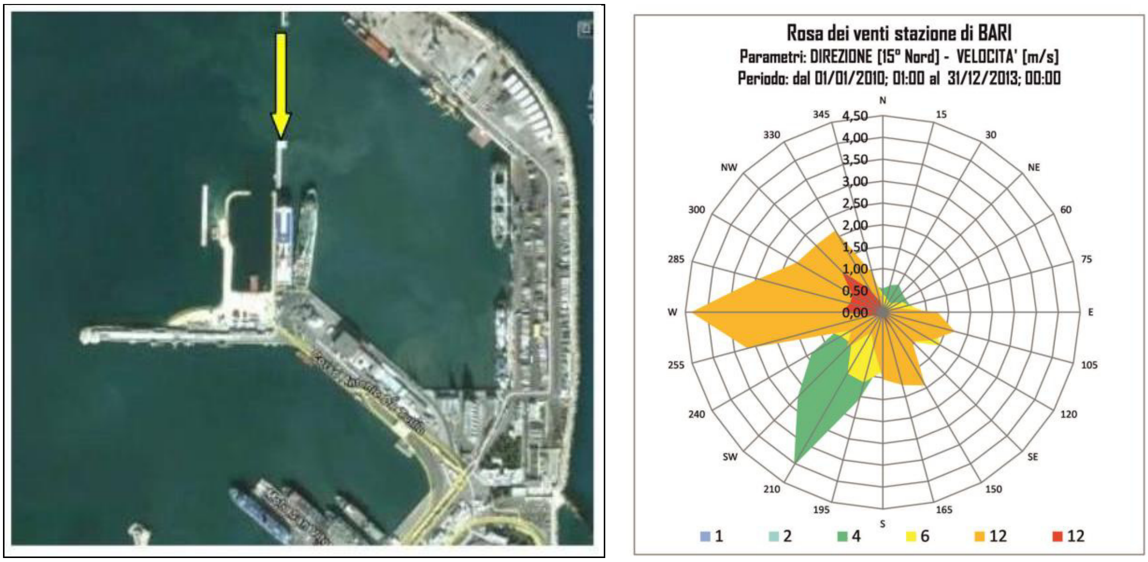

Fig. 1. (a) location of the wind meter in the Bari harbor; (b) annual wind rose for Bari station at 10m height

3. Methods used to obtain the wind vertical structure

The wind speed profile in the atmospheric surface layer is commonly described by Monin-Obukhov theory. In homogenous and stationary flow conditions, it predicts a log-linear profile:

$$u(z) = \frac{u^*}{k}\left[\ln\left(\frac{z}{z_o}\right) - \psi_m\left(\frac{z}{L}\right) - \psi_m\left(\frac{z_o}{L}\right)\right] \tag{1}$$

where κ denotes the von Karman constant, (taken as 0.4) and ψ_m is a universal stability function. Thus, if the wind speed is known at one height, the vertical wind speed profile is determined by two parameters: the surface roughness z_0 and the Monin-Obukhov stability parameter L.

$$L = -\frac{\rho\, C_p\, T\, u^{*3}}{kgH} \tag{2}$$

In eq. (2), C_p is the specific heat at constant pressure, T is the air temperature, H is the sensible heat flux. From eq. (1) and (2), u* and L can be solved by iteration, when T, H, z_o and $u(z)$ are known.

The Obukhov stability parameter L is used to define atmospheric stability. The non-dimensional parameter $\zeta=z/L$ is positive for stable conditions, negative for unstable and almost zero for near-neutral conditions. To solve u* and L we adopted the bulk method, which implies the least experimental effort, that is a wind speed measurement at one height, water and air temperatures to calculate the bulk Richardson number, which is then related to L [6].

In this paper the M-O theory has been first used alone, and then taking properly into account the sea surface roughness which influences the prediction of the wind profile. In the M-O model alone, a constant roughness the assumption of a constant sea surface roughness has been used, with a value of z0=0.2 mm. In the M-O theory modified for the sea surface roughness, we used the is the Charnock relation which takes into account the wave field by its dependence on friction velocity u* [1]:

$$z_o = z_{ch} \frac{u^{*2}}{g \cdot} \tag{3}$$

The Charnock relation works well for the open ocean, but for coastal areas it was found that the Charnock parameter is site specific, due to the influence of other physical variables like fetch on the wave field. A fetch dependent model for the Charnock parameter has therefore been developed, through the following relations

$$z_{ch} = A\left(\frac{C_p}{u^* \cdot}\right)^B \tag{4}$$

where C_p/u^* is the wave age, that is the ratio of the peak wave component celerity Cp and the friction velocity u*. The values for the empirical constants A and B are taken as A=1,89 and B=-1,59 [3].

Kahma and Calkoen [7] found the following empirical relation between the dimensionless peak frequency and the dimensionless fetch:

$$\frac{u^*}{g}\omega_p = C\left(\frac{g}{u^{*2}}x\right)^D \tag{5}$$

where ω_p is the peak wave frequency and x the fetch in metres. Values of C=3.08 and D= -0.27 have been used for the coefficients [7].

The influence of fetch on wave parameters for the considered site were determined through these relations, by the evaluation of an effective fetch for a given direction, calculated as the integral over all direction from α= -90º to α= +90º, weighted by a cosine squared term, normalised and divided by the fetch which would result from a straight coastline

$$x_{eff} = 2\int_{-\pi/2}^{\pi/2} \frac{x(\phi-\varphi)\cos^2(\phi-\varphi)d\varphi}{4/\pi} \tag{6}$$

With the transformation of eq. (5) the equation (4) for the Charnock parameter becomes:

$$z_{ch} = AC^B\left(\frac{gx_{eff}}{u^{*2}}\right)^{BD} \tag{7}$$

4. Results

4.1. Wind velocity distribution

As mentioned above, the occurrence frequencies of wind speed obtained directly by the measurements at the height z = 10m are substantially modified by the transformation of wind speed with altitude, estimated by the theory of Monin-Obhukov, and through the theory of Charnock which takes into account the lower roughness of the sea surface.

From the comparison between the wind rose assessed at z=85 m with the model of M-O and with that of Charnock (Fig. 2a, b) a significant increase in the frequency of wind speeds exceeding 12 m/s has been observed. These winds come from the sea (from directions between 270 °N and 315 °N), and the increase of the higher speed class occurs at the expense of the class immediately below.

The examination of fig. 2a and b gives evidence that the difference between the two models used for the estimation is apparent for the winds blowing from the sea, which are the ones with higher speed. In this regard, although the percentage of the winds coming from the ground (60.84%) is greater than that of the winds coming from the sea (39,17%), the contribution of the latter to the whole directional distribution at the site of Bari is of considerable importance, because of their higher speeds. This feature is captured by the model MO with Charnock roughness for the directions of the sea winds (coming from 255°-270°- 285°N, and coming from 300°-345°N).

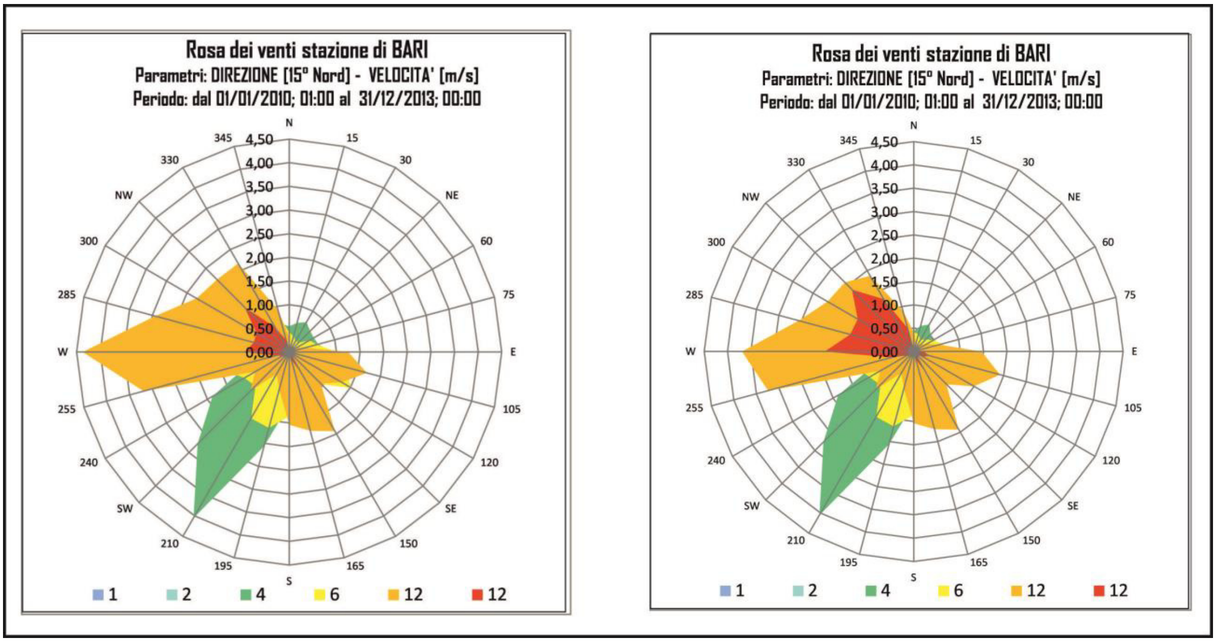

Fig. 2. (a) annual wind rose with M-O model at 85m height; (b) annual wind rose with M-O and Charnock model at 85m height

The percentage increase is even more visible in the histogram of fig. 3, which reports the data directly obtained from the measurements, and of fig. 4 a,b which reports the comparison between the results obtained by the two models. With regard to the winds from the direction 270 °N, the use of the Charnock model increases the percentage of wind speeds greater than 12 m/s from 1% to 2%, with an increase of 100%, while the same overall percentage of 8% is recorded. Similar increases happen to winds coming from the directions 285, 300, 315 and 330°N, all classes of wind directions coming from the sea. This happens at the expense of the class of wind speed immediately lower (speed between 6 and 12 m/s).

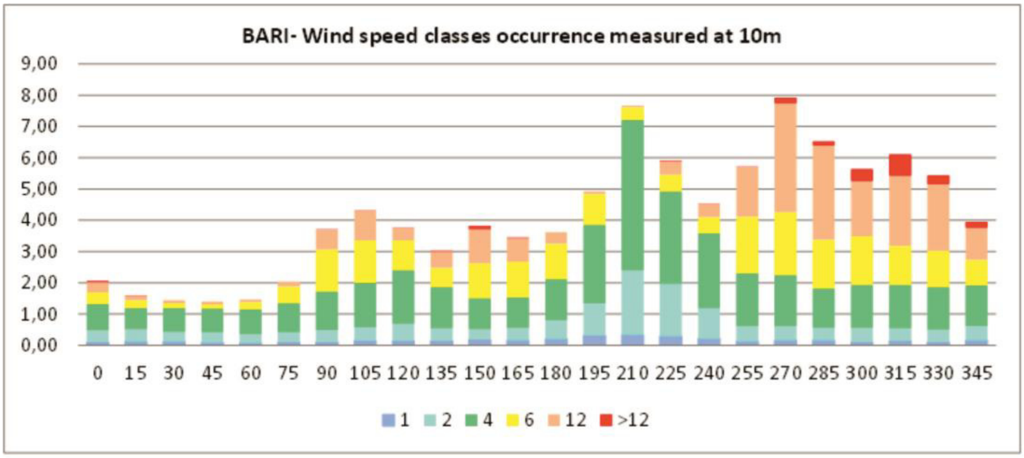

Fig. 3. Wind speed classes occurrence obtained directly from 10m height data

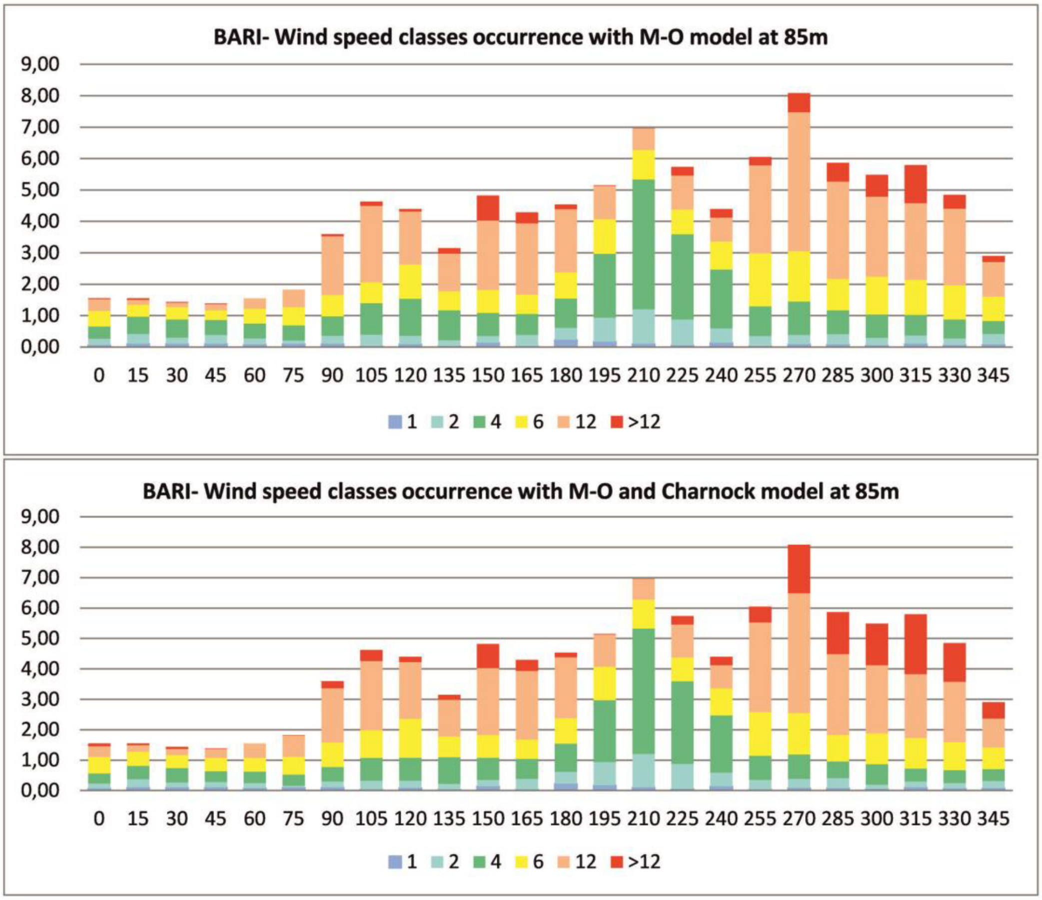

Fig. 4. Wind speed classes occurrence obtained at 85m height with a) M-O model; (b) M-O and Charnock model

4.2. Potential site productivity

The potential site productivity was established on the basis of the wind speed distribution function for different heights (site specific) and the test power curve and capacity factor of the wind turbine considered, as a function of the wind speed at the nacelle height (machine specific), reported in fig. 5 a,b for a target wind turbine (Enercorn E-82 E3 , 3 kw nom. pow).

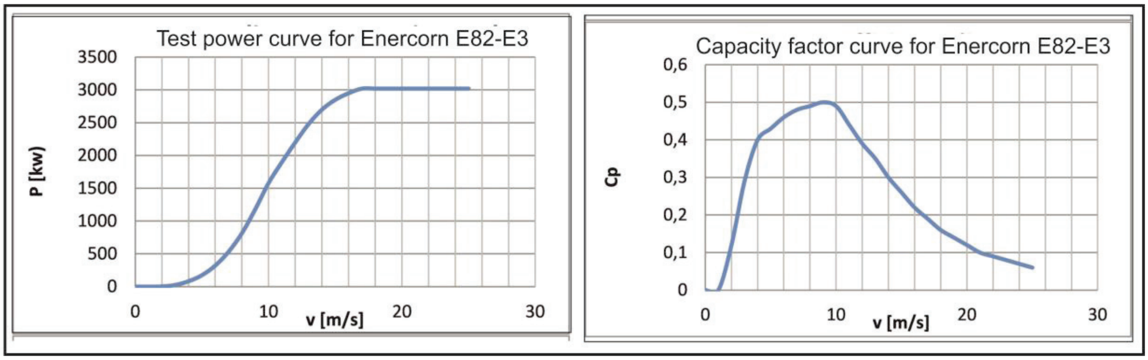

Fig. 5. Test power curve (a) and capacity factor (b) for a target wind turbine

4.3. Influence on the power productivity

The power production of a target wind turbine with hub height at 85 m and 3 MW rated power output was estimated from the wind speed measurement at 10 m height using the different methods (M-O and Charnock) described before. The estimated gross annual energy production was then compared in fig. 6 a,b.

The comparison shows that the M-O model with the Charnock approximation for the sea roughness length gives, with reference to the site of Bari, an estimate of power productivity on an annual basis for the single wind machine of about 30% higher than that the one estimated with the M-O with constant roughness.

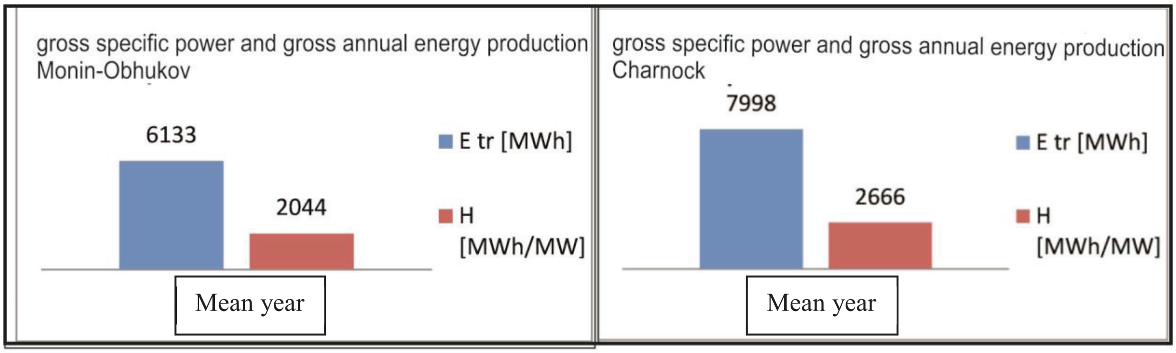

Fig. 6. (a) Wind power productivity with M-O model; (b) Wind power productivity with M-O and Charnock model

5. Conclusions

In this paper the vertical wind profile has been described by Monin-Obukhov theory and different models have been applied for the estimation of the two parameters used in this description: the Obukhov length and the sea surface roughness. Significant deviations between the constant roughness length and the variable one due to the sea winds have been found in all cases, and particularly in winter. In order to test the different models, the wind speed at 85 m height has been extrapolated from the measurement at 10 m height, which has been converted into power production estimates in order to investigate the importance of the differences for wind power output estimations.

The results show that the very simple assumption of a constant roughness leads to significant underestimations, particularly for winds coming from sea, and that the wind resource estimation at offshore sites is more complex than usually believed. Currently these conclusions have to be validated with other offshore wind measurements, which will be soon available in the next future.

References

[1] Monin, A. S. and Obukhov, A. M..‘Basic Laws of Turbulent Mixing in the Ground Layer of the Atmosphere’, Trans. Geophys. Inst. Akad. Nauk. USSR 1954, 151, 163–187.

[2] H. Charnock, 1955. Wind stress over a water surface, Quart. J. Roy. Meteor. Soc. 1955, 81, 639-640.

[3] H.K. Johnson, J. Højstrup, H.J. Vested, S.E. Larsen. On the dependence of sea surface roughness on wind waves, J. Phys. Oceanogr. 1998, 28, 1702-1716.

[4] P.K. Taylor, M.J. Yelland. The dependence of sea surface roughness on the height and steepness of the waves, J. Phys. Oceanogr. 2001, 31 572-590.

[5] B. Lange, J. Højstrup, S.E. Larsen, R.J. Barthelmie. A fetch dependent model of sea surface roughness for offshore wind power utilisation, in: P. Helm, A. Zervos (eds.), Wind Energy for the new millennium. Proceedings of the European Wind Energy Conference,WIP, 2001, Munich and ETA, 830-833.

[6] Garratt JR. The atmospheric boundary layer. Cambridge University Press, 1994.

[7] K.K. Kahma, C.J. Calkoen. Reconciling discrepancies in the observed growth of wind-generated waves, J. Phys. Oceanogr. 1992, 22, 1389-1405.