Numerical study on the Wave Boundary Layer, its interaction with turbulence and consequences on the wind energy resource in the offshore environment.

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Abstract.

The wind energy farming in the offshore environment is characterized by ever-increasing structures and costs, for which reducing structural damage and maximizing production become an imperative. Such challenge is faced by site planning, intelligent design and active control systems that ultimately require a fine Atmospheric Boundary Layer (ABL) description. Contributing to refine the wind flow description in the offshore environment for engineering purposes, this work considers: (i) The interaction between turbulent and Wave Induced fluctuations, pronounced in the lower portion of the Marine ABL (MALB): Region so-called Wave Boundary Layer (WBL); (ii) The impact of the WBL in the flow above it.

Focusing in the MALB sustained by non-equilibrium old-seas in neutral atmospheric conditions, the free-surface position and velocities are here prescribed into a Large Eddy Simulation (LES) according to a fifth order Stokes solution. The swell disturbances on the WBL are explored through mean profiles and spectral analyses. An original definition of the Wave Induced flow is presented, considering correlated turbulent and Wave Induced motions thus accessing the coupled dynamics between those fields and allowing the evaluation of the WBL height. Employing the proposed decomposition, the turbulent flow characteristics are recovered as expected in a flat bottom ABL, though some of its scales change considerably, forced by the WBL existent below.

1. Introduction

In coastal areas, the wind energy industry migrates to the offshore environment, where huge spaces are available in stronger and better behaved wind conditions. The offshore environment imposes new challenges to a well established wind energy industry. Increasing the distance to the coast and water depths leads to significant rise in operational costs that are sustained through increasing production and more efficient engineering. It is imperative to accurately predict and describe the offshore wind resource in order to propose cost efficient solutions, as one can then act in site planning, design and operational phases to maximize production and reduce costs. The concerned flow is characterized by a turbulent Atmospheric Boundary Layer (ABL) where the ocean’s dynamics significantly alter the atmospheric flow through higher heat capacity and complex wind-wave interactions that are important in fairly common situations. The ABL is mostly disturbed on a limited region referred as the wave boundary layer (WBL).

In a preliminary approach the wind-wave interaction has been subject to numerous theoretical studies describing the wave growth phenomena, noting the pioneer works of [1], [2], [3], [4],
Multiple field measuring campaigns are nowadays available forming the basis to comprehensive conclusions about the marine ABL, such as: FINO1 explored and described in [7] and [8]; ASIT in [8]; CBLAST and others in [9]. Global atmospheric forecast systems such as the ECMWF, improved in its Marine ABL (MABL) model by [10], are forced to use, at their finest, grid resolutions of tens of kilometers, requiring high level of modeling including the momentum transfer with the WBL. Modelling the wave effect on the upper part of the ABL where MOST is expected to hold, Charnock’s parametrization [11] is followed by many, s.a. reviewed and extended by [12], [9], [7] and [8].

To afford multiple scenarios and real time applications, prediction tools for design and operational purposes rely on semi-empirical and low-fidelity numerical solutions. State-of-the-art wind models adopted in solvers like HAWC2 [13] consider a mean wind log-law profile based on the Monin-Obukhov Similarity Theory (MOST) [14] superposed to randomly generated turbulent components with statistics given, e.g. by the Mann spectra [15]. It is observed though, that the mean wind profiles and its turbulent statistics considerably deviate from MOST and Mann’s predictions on the vicinity of ocean waves. The wave induced disturbances extend into limited regions above the free surface (c.f. [16], [17]) in the so called Wave Boundary Layer (WBL), which definition is not unique. Forced by this inner layer, the outer mean flow would behave similarly to static atmospheric flows such as usually described by MOST and Mann’s models, and the investigation of the WBL at local scales is thus desired to improve low-fidelity MABL models.

Modelling turbulence effects in the average flow, (Unsteady) RANS one or two equation closures are yet the most applied type of numerical model into CFD simulations of ABL flows at local scales ([18], [19]). Fully resolved turbulence is achievable through Direct Numerical Simulations (DNS) with limited Reynolds numbers, and has been employed, e.g. in [20]: Later developed into the Large Eddy Simulation (LES) model ([21], [22]) here employed to resolve the ABL flow in the absence of buoyancy forces. The LES approach introduces limited level of modeling into the isotropic, smallest turbulent scales, resolving most of the turbulent energy and especially the anisotropic motions determined by the problem boundary conditions.

When a swell aligns to slow winds, the momentum transfer occurs from the sea into the atmosphere in a situation referred as old seas, opposed to the wave growing phase referred as young seas. The momentum transfer is observed to be correlated to the deviations from MOST ([21]), and become important in young and old seas. The focus here is on the canonical case of neutral ABL, where a swell labeled by its phase velocity \( c \) encounters light wind conditions with initial wall stress \( \tau_w \), specific mass \( \rho \) and mean friction velocity \( u^*_0 = \sqrt{\tau_w/\rho} \). Such case is characterized by high wave ages \( WA = c/u^*_0 \) (Old-seas) and strong disturbances in the wind field, as the WBL extension is somehow proportional to the wave’s length.

Current study employs the deterministic numerical tool presented in [23] coupling air and water domains’ resolutions: The Large Eddy Simulation (LES) presented in [22] resolves a fully turbulent and incompressible fluid on the atmosphere; The High Order Spectral (HOS) method [24] resolves the non-linear potential waves’ equations on the free-surface. Focusing in the WBL generated by non-equilibrium old-seas in neutral ABLs, the free-surface position and velocities are here prescribed (5th order solution [25]) as boundary conditions into the LES and buoyancy forces are neglected. The governing equations, numerical strategy, results and conclusion follow respectively in sections 2, 3, 4 and 5. Mean vertical profiles in section 4.1 demonstrate significant disturbance of the ABL in the wave’s vicinity, which for some quantities surpasses the height of the WBL. The WBL definition and characterization are possible due to the methodologies presented in section 4.2, including an original definition of the Wave Induced (WI) Flow and the WBL height. The WBL characterization allows the investigation of turbulent motions in section 4.3, revealing diminished turbulent scales due to WI and turbulent interactions.
2. Governing equations

An incompressible and fully turbulent flow is considered with the Boussinesq approximation ([26]) acting in the buoyant terms of momentum and turbulent equations. Coriolis forces are neglected. The balance equations are filtered according to an LES approach. Let $u(x,t) = (u, v, w)$ and $p(x,t)$ be the spatially filtered velocity and pressure fields; $u^{SGS}$ and $p^{SGS}$ the residual fields; $p^* = p + (2\epsilon/3)$ the modified pressure accounting for the residual turbulent kinetic energy ($\epsilon = u_i^{SGS}u_i^{SGS}/2$) effect; $\rho(x,t) = -\rho_\infty(\theta - \theta_\infty)/\theta_\infty$ the specific mass dependent on the virtual temperature $\theta$ and the reference values $[\rho_\infty, \theta_\infty]$; $S = [\nabla u + (\nabla u)^T]/2$ the strain rate tensor; $\tau^{SGS} = -2\nu_t S$ the sub-grid-scale modeled shear stress tensor defined within the eddy viscosity hypothesis scope and dependent on the turbulent viscosity $\nu_t$; $g$ the gravitational acceleration. Mass and momentum balances are written as equations 1 and 2, and the residual turbulent kinetic energy modeled by the Deardorff single equation 3:

$$\frac{\partial u_j}{\partial x_j} = 0,$$

$$\frac{\partial u_i}{\partial t} + \frac{\partial(u_j u_i)}{\partial x_j} = -\frac{1}{\rho_\infty} \frac{\partial p^*}{\partial x_i} - \frac{\partial \tau^{SGS}_{ij}}{\partial x_j} - \frac{\rho}{\rho_\infty} g \delta_{ij}, \quad \text{and}$$

$$\frac{\partial e}{\partial t} + \frac{\partial(u_i e)}{\partial x_i} = (2\nu_t S_{ij})S_{ij} - \frac{g}{\theta_\infty} \nu_t \frac{\partial \theta}{\partial x_j} + \frac{\partial}{\partial x_j} \left( 2\nu_t \frac{\partial e}{\partial x_j} \right) - \epsilon. \quad (3)$$

The turbulent dissipation $\epsilon = c_e e^{3/2}/\Delta_f$ is determined according to the filter length scale $\Delta_f = [(3/2)^2\Delta x_1 \Delta x_2 \Delta x_3]^{1/3}$. The turbulent kinematic viscosity and diffusivity are respectively $\nu_t = c_k l e^{1/2}$ and $\nu_t = (1 + 2l/\Delta_f)\nu_t$, where $l$ is here equal to $\Delta_f$. The governing equations are transformed from the deformed moving grid into the cartesian numerical space and the full set of equations presented with the constants values, e.g., in [21].

3. Numerical strategy

The governing equations are solved in a moving grid by the pseudo-spectral numerical method given in [21]. The physical space $(x_1, x_2, x_3) = (x, y, z)$ is mapped into the computational space $(\xi = x, \eta = y, \zeta = \zeta(x, y, t))$. The pseudo-spectral discretization applies to $(\xi, \eta)$ directions and a second order finite difference to $\zeta$ direction. Given the characteristic length $\lambda$, the considered domain has size $(L_x, L_y, L_z) = (4, 2, 5)\lambda$ and is discretized with $(256, 128, 80)$ cells sized $(\Delta x, \Delta y, \Delta z)$ respectively. The cells are equally distributed in $(x, y)$ but not in $z$ where it grows according to an algebraic mapping: The first grid size in $z$ direction is $5.208 \cdot 10^{-3} \lambda$ and it grows with a constant ratio of 1.05. The third-order Runge-Kutta time-stepping scheme is employed with adaptive time step $(\Delta t)$, so that CFL = $\Delta t \cdot \max(u/\Delta x, v/\Delta y, w/\Delta z) = 0.5$. A uniform pressure gradient acts in $x$ direction driving the flow and in flat terrains the stresses’ integral balance in the boundaries gives the theoretical friction velocity $u_0^*$. For the neutral stability condition considered the difference between the first cell and surface tangential and normal velocities $(\Delta u_{[\xi,\eta]} \Delta u_{[\zeta]})$ are given by a log-law wall-function boundary condition (BC): $\Delta u_{[\xi,\eta]} = (u_{[\xi,\eta]}^*/\kappa) \ln(z/z_0)$ and $\Delta u_{[\zeta]} = 0$ with roughness length $z_0 = 10^{-6}\lambda$ and von Karman constant $\kappa = 0.4$. The friction velocity $u_{[\xi,\eta]}^*$ is obtained point-wise from turbulent resolved and modeled stresses. Residual turbulent kinetic energy flux in the surface and all fluxes in the upper boundary are null, except for the vertical velocities which are null instead of their fluxes as a no penetration condition is prescribed in the upper boundary. These
upper BCs in the absence of buoyant forces impose the boundary layer height \( \delta = L_z \). Periodic BCs naturally follow from the pseudo-spectral approach in \((\xi, \eta)\) directions.

Two cases are presented: Case 01 is the reference considering a flat terrain, while case 02 introduce the wind-aligned wave. The free-surface position and velocities are prescribed according to the fifth order Stokes solution given in [25]. The wave length equals the characteristic length scale \( \lambda = 2\pi/k \) and the non-dimensional wave height is \( ka = 0.2 \). The dispersion equation in deep water gives phase velocity \( c = \sqrt{g/\bar{k}} \) (Swell period \( T_s = \lambda/c \)) setting the relation between characteristic length and velocity scales with \( WA = c/u_0^* = 60 \). The turbulent characteristic time-scale is \( T_0 = \lambda/u_0^* = 60 T_s \). Exemplifying for a wave length \( \lambda = 300 \) m, the wave amplitude is \( a = 9.55 \) m, and the phase velocity \( c = 21.64 \) m/s \( (T_s = 13.86s) \): The reference friction velocity is thus \( u_0^* = 0.36 \) m/s and the characteristic time-scale \( T_0 = 13.86 \) min.

Originally the flow field is constructed from mean theoretical solution for flat plate turbulent boundary layers superposed to artificial, randomly generated turbulent motions. The initialization procedure then considers the buoyant effects on the momentum equations to generate resolved turbulence as further initial solution. The results here presented follow from a converged restart after buoyant terms are set back to zero representing neutral stratification. The wave forcing in the lower BC linearly evolves from null till its 5th order solution in \( 15T_s = 0.25T_0 \).

4. Results

4.1. Mean profiles
A spatial average, denoted by \( \langle C_{ij}[\xi,\eta] \rangle \), is applied through each \((\xi, \eta)\) horizontal computational plane and followed by a moving time average through the period \( \tau_{avg} = 38 T_0 \) for the quantities presented in this section, with the total average operator denoted by \( (\bar{\tau}) \). Fluctuations \( \langle \tau \rangle \) are obtained deducing resolved fields from their spatial averages so that \( u = \bar{u}_{\xi,\eta} + u' \). The friction velocity \( u_{\xi,\eta}^* = (\bar{\tau}_{w,\xi,\eta}/\rho)^{1/2} \) is obtained in the first grid cell summing resolved and modeled turbulent shear stresses \( \tau_{ij}^w = u'_i u'_j (1 - \delta_{ij}) + \tau_{ij}^{SGS} \delta_{ij} \) and its averaged history \( \bar{u}^* = ||u^*|| \) presented in figure 1 for each test case. The introduction of a prescribed swell in the first steps of figure 1 suddenly decreases the friction velocity at the surface: An effect which is reduced as the wind field adapts to the wavy lower condition. Statistical convergence have been observed for each quantity presented in this paper, which are probed in the final steps of figure 1.

A log-law \( \bar{u}_1 = (C_d u^* / \kappa) \ln(z/|\alpha z0|) \) with parameters \( [C_d/\kappa, \alpha] \) is fitted into the wind profile minimizing the integral root-mean-square difference \( RMSE_{diff} = \left[ \int_0^{z_{max}} (u_{FIT} - u)^2 dz/z_{max} \right]^{0.5} \) for \( z < 0.2\delta \) with obtained quantities shown in table 1. The fitting behavior may be appreciated in figure 2 where the wave introduce a pronounced disturbance of the log-law in the near region. The flat B.C. case closely reproduce the theoretical values for a neutral flat bottom ABL with the imposed B.C., i.e., \( C_d/\kappa = 0.4^{-1} \); \( \alpha = 1 \). The mean wind profiles are shown in figure 3a superposed to the ESDU standard [27]. The wind profiles are a linear combination of log and linear functions, which match quite accurately the ESDU prediction \( \bar{u}_1 = 2.5 u^* \ln(z/|\alpha z0|) + 34.5 f z/u^* \) with \( f = u^*/[60] \) for the flat
bottom case; the wave propagation effectively drags and speeds-up the mean wind along the ABL.

Mean turbulent profiles are exemplified from figures 3b to 3f. The turbulent kinetic energy (TKE = 0.5u′i′u′j′) is shown in figure 3b. Through the introduction of waves the TKE is greatly increased on the wave’s vicinity where the Wave Induced flow is clearly dominant, trending to non-disturbed values when \( z \sim 0.3\lambda \). The respective contribution from longitudinal and vertical velocities to the TKE is seen through the normal stresses (\( \sigma_{ii}^2 = \bar{u}_i' \bar{u}_i' \)) profiles in figure 3c where vertical velocities disturbances propagates further in the ABL. The rise in \( \sigma_{ii}^2 \) is rapidly damped, and the turbulence intensity (\( \sigma_{ii}/\bar{u}^2 \) at figure 3d) indicates lower level of turbulence through most of the ABL due to the increase of \( \bar{u}_1 \) not followed by the expected scaling of \( \sigma_{ii}^2 \).

Table 1: \( \bar{u}_1 = \frac{C_d u^*}{\kappa} \ln \left( \frac{z}{\alpha z_0} \right) \): Optimal \( \left[ \frac{C_d}{\kappa}, \alpha \right] \) for \( \min(RMS_{diff}) \) in \( z < 0.2\delta \).

| Case          | RMS_{diff}/u_0^* | \( C_d(\kappa = 0.4) \) | \( C_d(\kappa = 1) \) | \( \alpha \) |
|---------------|-------------------|--------------------------|--------------------------|---------|
| Flat B.C.     | 0.24              | 1.10                     | 0.38                     | 1.17    |
| Wavy B.C.     | 1.90              | 1.51                     | 0.28                     | 1.06    |

Main source of momentum flux along \( z \), the cross-correlations (\( 0.5\bar{w}'\bar{w}' + \tau_{13}^{SGS} \)) are exposed in figure 3e, being considerably increased up to \( z > \lambda \) due to the moving bottom. It is known that the rise in \( \bar{u}'\bar{w}' \) is consequent to the upward momentum flux related to the drag ([21]) shown in

Figure 3: Mean turbulent profiles.
4.2. Wave Induced motions
The general one dimensional correlation function of two variables $\phi_1$ and $\phi_2$ is $R_{\phi_1\phi_2}(r)$ and the one-dimensional spectral density function $E_{\phi_1\phi_2}(k)$ twice its Fourier transform where $k = 2\pi/r$. The spectra are here evaluated in each horizontal computational plane along $\xi$ direction and averaged through $[\xi, \eta, t]$ with $t_{avg} = 13T_0$, so that $E = E(\zeta, k)$. The spectra are first exemplified in figures 4a and 4b by the fluctuating kinetic energy spectral density functions $E_{u-\overline{u}r}[u-\overline{u}]$ evaluated in different horizontal planes. The wave signature is evident, leading to peaks occurring in the swell free ($k_w$) and bounded ($nk_w$; $n = 2.5$) wave numbers that are gradually damped with increasing height.

For a deterministic assessment of the wave induced perturbations, it is useful to consider a triple decomposition, where a generic flow field $\phi$ (Such as velocity and pressure) decompose into $\phi = \overline{\phi} + \phi'$ and $\phi$ the turbulent and wave related fields. Imposing a filter to retain the Wave Coherent flow ($\phi = \overline{\phi} + \phi^C + \phi^{t}$) that neglects its correlation with turbulence, [28] presents dynamic equations for the decomposed fields uncoupled between Wave Coherent ($\phi^C$) and turbulent ($\phi^{t}$) motions. This methodology led to fruitful conclusions about the WBL, e.g. in [28] and [29] that define the filter projecting a time signal $[u(t), p(t)]$ into the vector space of all wave coherent signals, i.e., those occurring at the same frequencies as the wave profile $\eta(t)$. Alternatively the present study employ the Wave Coherent filter (Eq. 4) in space. Let $\overline{\eta}_k(x)$ be the in-quadrature counterpart of the $k^{th}$ wave number free surface elevation $\eta_k(x)$:

$$\phi^C(x, t) = \sum_k \left( \frac{\overline{\phi}(x, t)\eta_k(x, t)^{[x]}}{||\eta_k||^2} \eta_k(x, t) + \frac{\phi(x, t)\eta_k(x, t)^{[x]}}{||\eta_k||^2} \overline{\eta}_k(x, t) \right)$$

effectively filters flow features occurring with length scale $2\pi/k$, where $[x]$ and $|| \cdot ||$ indicate average and norm in $x$ direction. Considering the triple decomposition as in equation 4 filters not only wave-induced, but also turbulent fields which occur in the wave harmonics lengths, leading to non-physical gaps in the turbulent spectra (figure 4c). A flow dependent modification is then proposed to the Wave Coherent (WC) filter 4, thus renamed Wave Induced (WI) filter in eq. 5 such that $\phi = \overline{\phi} + \phi' + \phi^t$. Let $0 \leq f_{ki}^2(z) \leq 1$ be the fraction of wave induced energy in the total fluctuating energy ($E_{\phi'}/E_{[\phi-\overline{\phi}][\phi-\overline{\phi}]}$) contained in the wave number $k$ and velocity component $i$, the Wave Induced field is:

$$\phi'(x, t) = f_{ki}(z) \cdot \phi^C(x, t),$$

where $f$ should be determined considering turbulent and Wave Induced field specific characteristics, here based on the turbulent spectra such that $f_{ki}^2(z)$ minimizes the second derivative of turbulent velocities and pressure spectra in the wave filtered lengths scales. This particular strategy is suitable for regular seas but should be adapted otherwise, e.g. considering space-time spectra instead of space only. One shall refer to $\phi' + \overline{\phi}$ as the fluctuation field obtained through the usual Reynolds decomposition, where the turbulent field is $\phi'$ obtained after the filter defined by equations 4 or 5. The turbulent spectra obtained with the filters proposed by
equations 4 (WC filter) and 5 (WI filter) are superposed to the fluctuations’ spectra (No filter) in figure 4c.

Figure 4: One-dimensional spectral density function $E_{\phi_1\phi_2}(l=2\pi/k)$.

The filter proposed in equation 4 assumes Wave Coherent and turbulent motions are not correlated ($\langle \tilde{\cdot} \cdot \rangle' = 0$): A convenient property that allows the uncoupled form of their balance equations presented in [28], but which is lost with equation 5. It appears that Wave Induced and turbulent correlations are a key point into understanding the WBL behavior and the disturbance in turbulent motions: It is through these coupled dynamics’ that turbulent scales are distorted as Wave Induced motions merge into the turbulent cascade along the WBL.

Figure 5: squared root of the wave induced energy fraction $f_{\lambda_b}(z)$, defined in equation 5.

The obtained squared root of the wave induced energy fraction $f_{\lambda_b}(z)$ is shown in figure 5 for each of the decomposed fields and wave harmonics lengths. The decay with height is noted as $f$ smoothly decays from $f \sim 1$ up to $f \sim 0$, at $z \sim 0.6\lambda$ and $z \sim 0.8\lambda$ for longitudinal and vertical velocities, respectively. No Wave Induced flow is observed for transversal velocities, omitted for the sake of brevity. As pressure propagates with infinity speed in incompressible flows, the wave induced pressure rapidly reaches the top of the domain not being properly damped above the WBL. As a result Wave Induced flow dominate pressure fluctuations up until the domain’s vertical extension. The wave induced pressure oscillations on the upper surface are a non-desired but well known problem in high resolution CFD incompressible applications that involve oscillatory moving lower boundaries ([23]). The decay in $f_{k}$ is more rapid for lower wave numbers, but it is still unclear how much this is due to weaker BC’s wave forcing or the fluctuating behavior in those specific scales. A natural definition of the WBL height that
require negligible (< 1%) wave induced energy compared to the total energy in the principal wave number occurs when \( f < 0 \).

1. Leading to a WBL height of \( \sim 0.4 \lambda \) or \( \sim 0.6 \lambda \) if longitudinal or vertical motions are respectively considered.

### 4.3. Turbulent motions

![Graphs](attachment:graphs.png)

Figure 6: Turbulent spectra. Wavy (WI filter) and flat bottom cases with the ESDU reference.

Applying the wave related decomposition allows the comparison of wavy and flat B.C. cases turbulent motions through the turbulent spectra of figure 6 and their integral scales \( l_0(u') = \pi E_{ii}(0)/[2R_{ii}(0)] \) at figure 7. The WC and WI filters give meaning to turbulent motions and thus to the definition of integral length scales that otherwise (No filter) are hugely mistaken in figure 7a. A smaller improvement to the turbulent length scales is obtained with the WI filter (Further explored in figures 7b and 7c) compared to the WC filter. The resolved integral length scales \( l_0 \) are taken into the ESDU standard [27] as the reference spectra in figure 6. Vertical velocity spectra have been omitted but their integral length scales are reported in figure 7c.

![Graphs](attachment:graphs.png)

Figure 7: Integral length scale \( l_0 \).

The diminishing of turbulent integral scales by the wave’s introduction is observed in figures 7b and 7c up to \( \zeta > 0.5 \lambda \) as the Wave Induced alternated motions breaks down both wind and drag generated turbulent motions (Figure 8). The disturbance in turbulent spectra obtained with the waves’ introduction is explained by the coupling between turbulent and Wave Induced flows, only appreciated if \( \tilde{\zeta} \neq 0 \) as in eq. 5.
5. Conclusion

A canonical test case is presented where a reasonably sized swell ($ka = 0.2$), described by 5th order theoretical solution, meets relatively slow wind conditions ($WA = 60$) in the neutral MABL resolved by LES. It is shown that mean wind and turbulent quantities profiles might be disturbed at heights way above the WBL and into the exploitation zone of current offshore wind turbines.

An original methodology allows the characterization of the MABL into its Wave Induced and turbulent motions, considering the correlation between those fields, thus allowing further investigation of the coupled dynamics between them. The decomposition must rely on turbulent and wave induced characteristics to define the physical parameters $f$, here obtained to recover turbulent spectral density functions’ shapes as expected from classical flat terrain turbulent motions. This particular strategy is suitable for regular seas but should be adapted otherwise, e.g. considering space-time spectra instead of space only. A natural definition of the WBL height that require negligible ($< 1\%$) wave induced energy compared to the total energy in the principal wave number occurs when $f < 0.1$: Leading to a WBL height of $\sim 0.4\lambda$ or $\sim 0.6\lambda$ if longitudinal or vertical motions are respectively considered.

The Wave Induced filter proposed recover the expected turbulent behavior, though turbulent scales are distorted and particularly the integral scale is diminished. The wave induced and turbulent correlations explain how wave induced motions merge into the turbulent cascade distorting and forcing the turbulent flow above the WBL. Besides confirming the well known importance of drag and upward momentum flux, present results indicate statistical models of wind resource could improve their accuracy in offshore environments by considering (i) The distortion of turbulent scales and (ii) The superposition of a Wave Induced field model.

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