

Modeling wind farm noise emission and propagation: Effects of flow and layout

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ABSTRACT

This study demonstrates the influence of wind farm flow on noise generation and downstream propagation through numerical simulations. Time averaged flow fields, modeled using large-eddy simulations, serve as input to acoustic models that predict wind turbine noise. In the first turbine row, turbulent inflow noise and trailing-edge noise contribute equally, with turbulent inflow noise dominating at low frequencies and trailing-edge noise at higher frequencies. Farther downstream in the wind farm, trailing-edge noise's relative contribution decreases because the wind speed is lower, while turbulent inflow noise persists because turbulence levels remain high. These effects are more pronounced in aligned wind farms than in staggered layouts, given stronger wake interactions. However, staggered farms produce more noise overall because turbines operate at higher wind speeds. Additionally, wind farm flow significantly affects sound propagation downwind. Wake superposition changes sound focusing, modifying amplification areas compared to an isolated turbine. For a staggered layout, it particularly shows enhanced sound focusing downwind. This leads to higher sound levels and amplitude modulation downwind of the wind farm, compared to an aligned layout. These phenomena are not captured by models based on isolated turbines. These findings underscore the importance of integrating flow and acoustic models to more accurately assess the environmental impact of wind farms.

1. Introduction

The expansion of renewable energy has led to an increase in both onshore and offshore wind farms, which consist of multiple wind turbines operating in close proximity. The number of onshore wind farms is expected to keep increasing to reach Europe's energy production goals [1]. Hence, assessing wind turbine noise through simulation is crucial to mitigate its effects on residential areas. For accurate assessment, it is essential to consider both realistic sound power levels (SWL) and propagation effects. Previous studies have examined the effect of flow on sound propagation for an isolated turbine, and described a strong influence of atmospheric conditions on sound propagation [2,3], as well as an effect of the wind turbine wake on downwind propagation, leading to increased sound pressure level (SPL) in this direction [4].

However, flow conditions inside and around a wind farm can differ significantly from those around an isolated wind turbine, affecting both noise generation and propagation. Moreover, large wind farms can lead to the formation of an internal boundary layer, which modifies the atmospheric flow downwind [5,6]. Some studies have already contributed to the understanding of wind farm noise propagation. Shen

et al. [7] performed a detailed investigation of noise propagation in wind farms using parabolic equation (PE) simulation, accounting for realistic atmospheric flow and terrain features. Their study demonstrated that variations in the mean flow lead to substantial changes in sound pressure levels upstream and downstream, relative to those predicted using a logarithmic profile. Sun et al. [8] also used PE simulation for wind farm noise prediction and studied the effect of wake superposition in the downwind direction. They concluded that there is a combined effect of atmospheric conditions and wake effect on the downwind and upwind noise levels of a wind farm. However, their study was limited to downstream and upstream propagation directions and considered a simple source model.

Recent studies have explored joint optimization of wind farm layouts [9,10] or curtailment plans [11] to mitigate noise annoyance while maximizing energy production. However, the acoustic models used typically rely on point source modeling and basic propagation effects, such as ground reflection and atmospheric absorption, without accounting for refraction induced by the flow. A notable exception is the study by Nyborg et al. [11], which utilized comprehensive wind

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farm flow and acoustic simulations that incorporate wake effects to optimize curtailment strategies. Their findings demonstrate that integrating realistic noise propagation, specifically accounting for wind shear and wake interactions, enables the development of more efficient noise reduction plans.

Despite this previous work, comprehensive studies of wind farm noise propagation remain limited. Specifically, there has been a lack of comparisons between different wind farm layouts with extensive analysis of the potential effects arising from propagation inside a wind farm. Moreover, amplitude modulation (AM) are usually left out of the acoustic analysis while it has been reported multiple times [12,13] that they have an essential impact on the perception of wind turbine noise. Finally optimization studies [10] point out the need to use higher fidelity modeling to assess the results of the optimization procedure. This work aims to address these gaps by conducting a comparative study of wind farm noise propagation for different wind farm layouts. This is crucial to provide recommendations for the optimal layout of wind farms to minimize noise impacts.

The paper is organized as follow. Section 2 details the numerical methods employed to compute the noise from a wind farm. The different wind farm layouts are then introduced in Section 3. Initially, an isolated turbine case with a stable atmospheric boundary layer (ABL) is considered. Subsequently, aligned and staggered wind farm layouts are presented. The results are described in Section 4. First, the flow fields obtained for these three cases are shown in Section 4.1. Then, Sections 4.2 and 4.3 study the influence of the layout on the source levels and on the propagation, respectively. In Section 4.4, the overall sound pressure level (OASPL) and AM fields are compared between the different cases. Finally, concluding remarks are given in Section 5.

2. Methodology

The methodology used to compute wind turbine noise involves three main steps, consistent with the framework established in Colas et al. [14]. This approach aligns with recent advancements that improved predicted OASPL and AM accuracy, like using distributed sources rather than point sources [4,15] or incorporating realistic flow fields with a wave-based propagation method [4].

2.1. Flow

First, large-eddy simulations (LES) [16] are performed to obtain the average flow field. The concurrent precursor method [17] is employed and the wind turbines are modeled with an actuator disk method. This model was widely validated against field measurements and wind tunnel experiments [6]. Although the simulations capture unsteady dynamics, this study focuses only on the mean velocity fields $\mathbf{V}_0 = (u_0, v_0, w_0)$ and turbulence dissipation rate ϵ_0 , excluding turbulence scattering and unsteady effect even though it is known to impact wind turbine noise propagation [4].

2.2. Source model

The noise generated by each wind turbine is computed using the approach described in Tian and Cotté [18]. Initially, the free-field sound pressure level SPL_{ff} is calculated based on Amiet strip theory [19]. Each turbine blade is divided into several segments, treated as uncorrelated point sources. The trailing edge noise (TEN) and turbulent inflow noise (TIN) are computed for each segment at various angular positions, accounting for the blade geometry and the input mean flow [18,20]. The TIN depends on the local wind speed and turbulence dissipation rate encountered by each blade segment. The local wind speed at each blade segment is determined from the blade rotational speed Ω and the incoming wind speed u_0 . The turbulence dissipation rate ϵ_0 is computed directly from the LES results at each blade segment position. The TEN depends on the local wind speed and airfoil geometry. The

Table 1
Wind turbine control parameters [24].

	cut-in	rated	cut-out
u_{hub} (m.s ⁻¹)	3	11.4	25
Ω (rpm)	6.9	12.1	0

wall pressure fluctuation at the trailing edge is computed using the model developed by Lee and Shum [21] with boundary layer quantities computed using XFOil. The TIN and TEN models are applicable to the far field, defined as distances greater than the blade chord length and the acoustic wavelength. This type of model has been used in many wind turbine noise studies and has shown very good agreement with field measurements [22,23].

In this work the data provided for the NREL 5 MW wind turbine [24] is used to control Ω as a function of the wind speed sampled at the hub height (u_{hub}) of each turbine. The rotor speed increases from the cut-in wind speed to the rated where it is kept constant up to the cut-out wind speed (see Table 1).

2.3. Propagation model

The sound pressure level relative to the free-field ΔL is computed using a wide angle parabolic equation model (WAPE) which formulation is derived in Sec. V.A of Ostashev et al. [25] for an arbitrary moving medium using a high frequency approximation. It accounts for ground effects and atmospheric refraction on sound propagation. WAPE models have been validated against field measurements in the context of wind turbine noise propagation [26,27]. The WAPE is solved using a second-order finite-difference scheme in the z -direction and a Crank–Nicolson algorithm to advance the solution in the x -direction. Numerically, this involves inverting a tridiagonal matrix, which is done efficiently using the Thomas algorithm. The starting field is the second-order starter presented in Salomons [28], which represents a monopole source.

To optimize computational costs, ΔL is not calculated for each segment position. Instead, fictive source heights are assumed along a vertical line in the rotor plane passing through the turbine hub as described in Cotté [29]. The value of ΔL is interpolated linearly between the two closest fictive sources. For each turbine in the wind farm, simulations are performed for multiple propagation angles τ . The resulting 2D fields are interpolated onto a common 3D Cartesian grid.

2.4. Sound pressure level and amplitude modulation

The SPL at a receiver for one segment is given by

$$SPL^i(\mathbf{x}, f, \beta) = SPL_{ff}^i(\mathbf{x}, f, \beta) + \Delta L^i(\mathbf{x}, f, \beta) - \alpha(f)R, \quad (1)$$

where i denotes the segment index, \mathbf{x} the receiver coordinates, f the frequency, β the blade angle ($\beta = 0$ corresponds to the blade pointing upwards), α the atmospheric absorption coefficient, and R the distance from source to receiver.

The noise emitted by each segment is considered fully uncorrelated such that the SPL resulting from each blade segment can be summed logarithmically to obtain the sound from a full wind turbine. Similarly, in the case of a wind farm, the contributions of each turbine can be added logarithmically. When considering multiple turbines at different location, the propagation time must also be accounted for. Following the methodology from Mascarenhas et al. [20] the SPL as a function of the rotor angle is converted to an SPL as a function of time. The rotor is discretized with an angular step $\Delta\beta$ and the time domain is discretized with a time step Δt . Time signals of length $T_{tot} = 2\pi/\Omega$ are computed at each receiver position such that

$$SPL(\mathbf{x}, t_k, f) = 10 \log_{10} \left(\sum_{i=1}^{N_s} \sum_{j=1}^{N_\beta} 10^{SPL^i(\mathbf{x}, \beta_j, f)} \delta_{ijk} \right), \quad (2)$$

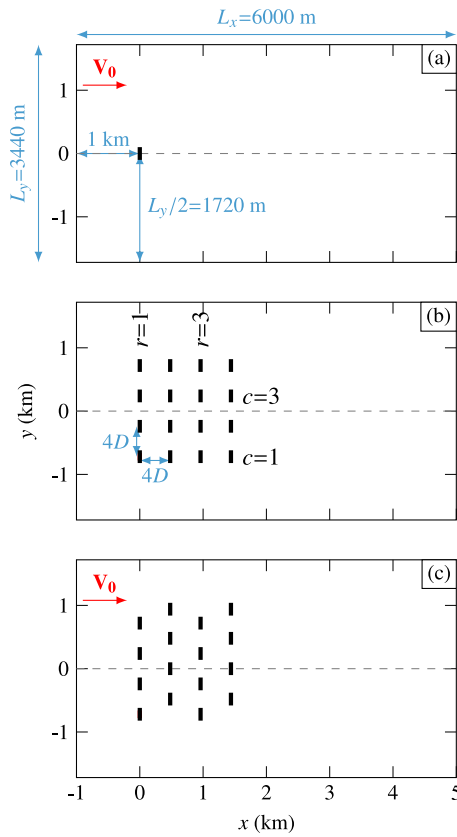


Fig. 1. Sketch of the LES domain for the different layouts. Wind turbines are indicated using thick lines. Note that the acoustic computational domain only extends up to $x = 5000$ m.

$$\delta_{ijk} = \begin{cases} 1, & \text{if } T_i^j \leq t_k < T_i^{j+1} \\ 0, & \text{otherwise,} \end{cases} \quad T_i^j = \frac{R_i^j(\mathbf{x})}{c_{\text{ref}}} + \frac{\beta_j}{\Omega}, \quad (3)$$

where Ω is the rotational speed in rad.s^{-1} , T_i^j is the time at which the sound emitted by a segment i at a position $\beta_j = j\Delta\beta$ reaches a receiver at \mathbf{x} , $t_k = k\Delta t$ is the discrete time, $R_i^j(\mathbf{x})$ is the distance between segment i at angle β_j and receiver \mathbf{x} , and c_{ref} is the sound speed at the ground. Note that this is an approximation as the sound speed is not consistent in the entire domain. A more accurate approximation, which was not implemented, would involve using the average sound speed along the path between each source-receiver pair. Note that if two turbines rotate at different speeds Ω the total time computed is different and hence a common multiple of the two periods must be used to recover a periodic signal.

Finally, the overall sound pressure level (OASPL) is obtained by integrating the SPL across the frequency band [14]. The averaged OASPL ($\overline{\text{OASPL}}$) and AM are computed over a complete rotor rotation as:

$$\overline{\text{OASPL}}(\mathbf{x}) = 10 \log_{10} \left(\frac{1}{N_t} \sum_k^{N_t} 10^{\text{OASPL}(\mathbf{x}, t_k)/10} \right), \quad (4)$$

$$\text{AM}(\mathbf{x}) = \max_t (\text{OASPL}(\mathbf{x}, t)) - \min_t (\text{OASPL}(\mathbf{x}, t)),$$

where N_t is the number of discrete time step for one rotor rotation.

3. Cases studied

Different scenarios are examined with a computational domain of $L_x = 6$ km, $L_y = 3.44$ km, and $L_z = 1$ km in the streamwise, spanwise, and vertical directions, see Fig. 1. To provide a reference, simulations

are performed with a single wind turbine and compared to aligned and staggered wind farm configurations comprising 4×4 turbines. The turbines have a diameter of $D = 120$ m and a hub height of $h_{\text{hub}} = 90$ m. In the aligned wind farm case, the inter-turbine spacing in the spanwise and streamwise direction is $4D = 480$ m. The thrust coefficient and induction factor for the actuator disk model are $C_T = 3/4$ and $a = 1/4$, respectively. Note that the columns of the wind farm are aligned with the flow direction while the rows are considered perpendicular to the flow. In the following, each row and column are referenced with index r and c , respectively. Hence, turbines are designated as t_r^c , such that t_1^1 corresponds to the turbine at $(x, y) = (0, -720)$ m.

The LES domain is discretized using a grid of $400 \times 220 \times 96$ points, yielding a resolution of $\Delta x = 15$ m, $\Delta y = 15.6$ m and $\Delta z = 10.4$ m. The surface roughness is set to $z_0 = 0.1$ m, a typical value used in acoustics for onshore conditions [28]. Stable boundary layer cases are simulated with a constant cooling rate equal to $C_L = -0.2 \text{ K.h}^{-1}$ applied at the ground. This atmospheric condition was selected because it typically represents the ideal scenario for AM prevalence and downwind sound refraction [30], which ultimately creates a worst-case scenario for noise annoyance. Simulations are run until a quasi-equilibrium state is reached, after which the flow fields are averaged over two hours to provide input for the source and propagation models.

Acoustic simulations are performed for each case, at frequencies ranging from 50 Hz to 1080 Hz with a grid step equal to a tenth of the wavelength, consistent with Colas et al. [31]. The wind turbine geometry is similar to the one developed by Cotté [29]. The rotor is discretized with an angular step of 10° , and each blade is divided into 8 segments. The propagation simulation is carried out using the $N \times 2\text{D-PE}$ propagation method. The variable-porosity model is used to model the ground impedance [32]. The effective flow resistivity is set to 50 kN.s.m^{-4} , and the effective porosity change rate is set to 100 m^{-1} , which reflect grassy ground conditions. Other soil conditions could modify the overall sound levels [2]. However, we expect relative variation between cases studied to stay the same.

An angular step of 2° is used to discretize the entire domain except in the downwind direction ($-16^\circ < \tau < 16^\circ$) where a 1° angular step is employed. The results are then interpolated on a Cartesian grid with $\Delta x = \Delta y = 10$ m. The propagation simulations are performed for 7 equivalent source heights to discretize the rotor plane [14].

4. Results

4.1. Flow fields

The streamwise velocity fields are illustrated in Figs. 2(a) and (c) for an isolated wind turbine. The figure shows that in these stable conditions, the low turbulence intensity leads to large velocity deficits and long wakes. Figs. 2(b) and (d) show that the turbulence dissipation rate increases inside the wake especially at the wake edges, where strong shear is present and reflects enhanced turbulent mixing.

Figs. 3(a, c) illustrate the streamwise velocity in the aligned wind farm. In this case, the second row experiences the largest velocity deficit, while partial wind speed recovery occurs in the third and fourth rows due to energy entrainment from above the wind farm. In Figs. 3(b) and (d), the turbulent dissipation rate is plotted for the planes $z = 90$ m and $y = -720$ m. The turbulent dissipation increases inside the wind farm similarly to the results for the single turbine. The increased mixing at the top of the farm, along with the associated rise in dissipation, explains the wind speed recovery after the second row. This increase of turbulence within the wind farm may also affect the sound emitted from the turbines.

The flow fields for the staggered case are shown in Fig. 4. Due to a larger spacing between turbines, the overall velocity deficit within the farm is reduced in Figs. 4(a) and (c). Similarly, the maximum value of the turbulence dissipation rate reached inside the farm is lower than for the aligned case. This staggered configuration is more representative

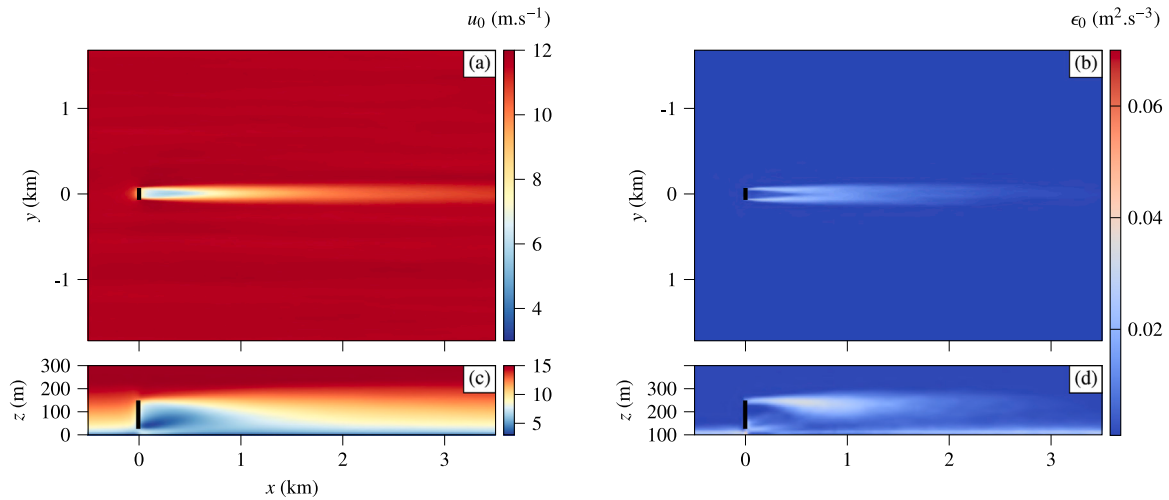


Fig. 2. Flow fields for the single turbine layout. (a) and (c) streamwise wind speed u_0 , (b) and (d) turbulence dissipation rate ϵ_0 for planes at (a) and (b) $z = 90$ m (hub height) and at (c) and (d) $y = 0$. The rotor position is shown with black lines.

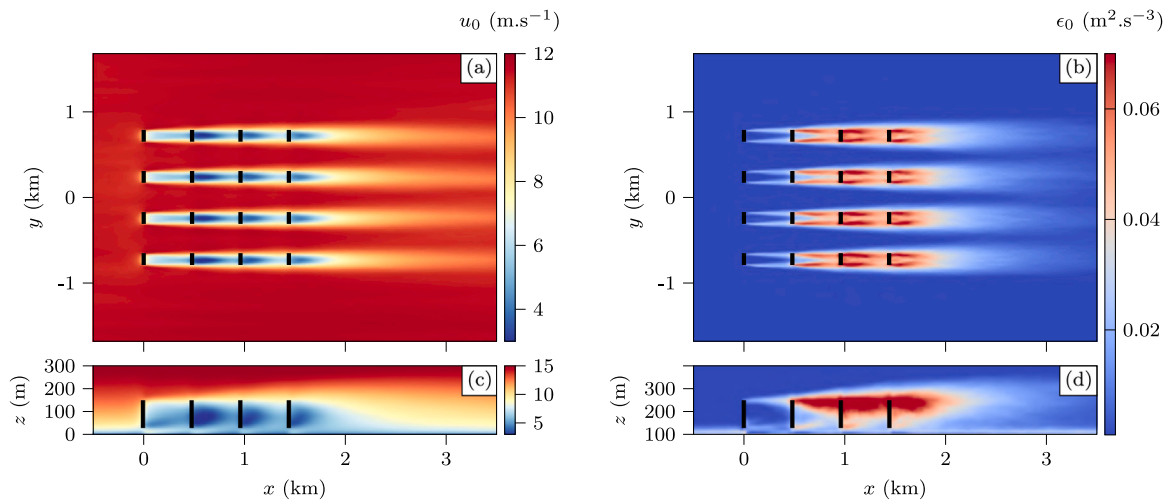


Fig. 3. Flow fields for the aligned layout and stable atmospheric condition. (a) and (c) streamwise wind speed u_0 , (b) and (d) turbulence dissipation rate ϵ_0 for planes at (a) and (b) $z = 90$ m (hub height) and at (c) and (d) $y = -720$ m. The rotor positions are shown with black lines.

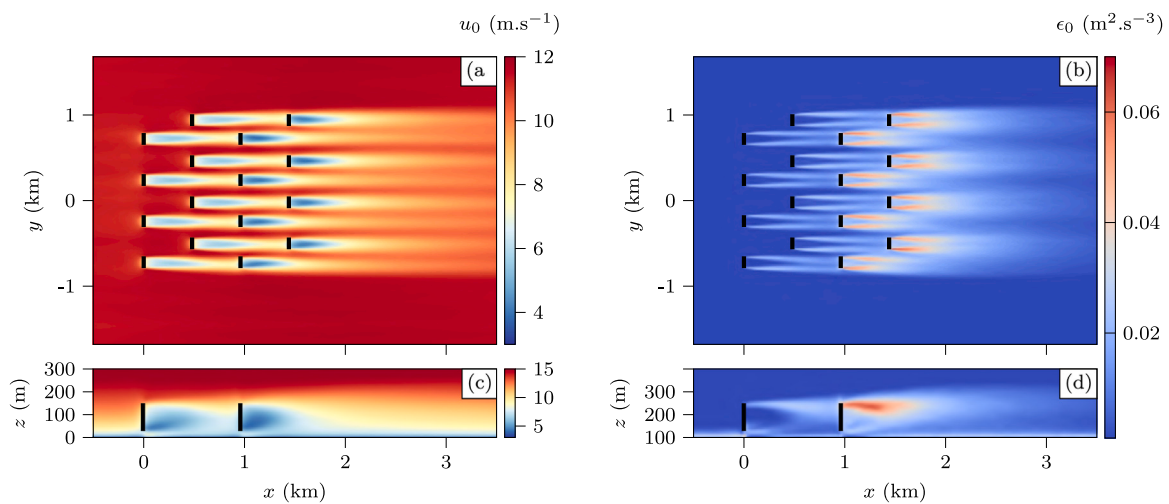


Fig. 4. Flow fields for the staggered layout and stable atmospheric condition. (a) and (c) streamwise wind speed u_0 , (b) and (d) turbulence dissipation rate ϵ_0 for planes at (a) and (b) $z = 90$ m (hub height) and at (c) and (d) $y = -720$ m. The rotor positions are shown with black lines.

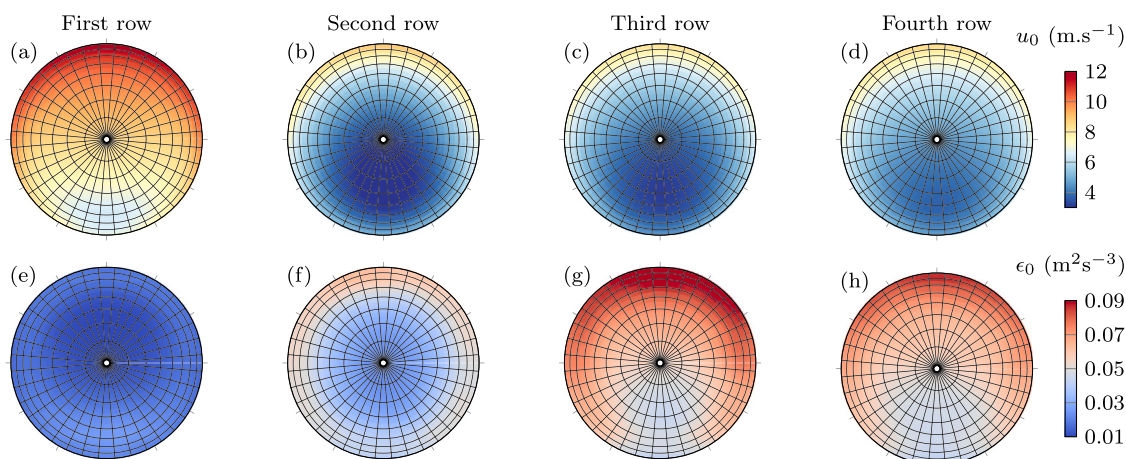


Fig. 5. Flow input for the source model for the aligned wind farm. Figures (a) to (d) show the wind speed and figures (e) to (h) the turbulent dissipation rate. Columns from left to right indicate results for first to fourth row. The rotor discretization for the source model is shown with black lines.

of actual wind farms than the aligned one, as it reduces wake effects between neighboring turbines.

Finally, Fig. 5 illustrates the mean wind speed and turbulence dissipation rate sampled at the rotor position in each row of the aligned wind farm. For conciseness, the flow sampled at the rotor for the staggered wind farm are not presented here. The wind velocity drops sharply between the first and second rows, followed by visible recovery in the third and fourth rows. Additionally, wind speed varies across the rotor plane. For all turbines, the ABL shear causes higher wind speeds at the top of the rotor and lower speeds at the bottom. Turbine flow blockage also influences wind speed, resulting in slightly higher wind speeds at the rotor edges compared to the center.

The turbulent dissipation rate ϵ_0 influences the TIN and is also depicted in Fig. 5. As previously noted ϵ_0 increases within the wind farm and hence increases from one row to the next. At the first rotor, we observe a more typical ABL structure, with slightly higher turbulence dissipation at the bottom of the turbine. For the third and fourth rows the turbulent dissipation rate is higher at the top of the rotor. This is due to the higher wind speeds, which induce stronger shear and enhanced wake mixing, leading to a higher turbulence dissipation rate.

4.2. Turbine noise emission

The flow input significantly influences the sound emitted by each wind turbine. First the model provides an effective overall sound power level of 102.5 dBA for the isolated wind turbine. The power levels are derived from the SPL in free field evaluated at a receiver 3 km downwind of the turbine, with corrections for the geometrical spreading [14]. Fig. 6(a) displays the overall source power for each turbine in the aligned wind farm relative to the isolated wind turbine. Turbines in the same row generate similar overall sound power levels (OASWL) within a 0.5 dBA margin. The first row ($r = 1$) has the highest sound power emission, with levels corresponding to the isolated case. Due to the substantial decrease in wind speed after the first row, which reduces the rotor's rotational speed, the second row ($r = 2$) shows the lowest sound power level. The OASWL of the third and fourth rows gradually increase as the wind speed recovers within the wind farm.

The frequency content of the produced noise also varies across the wind farm, as illustrated in Fig. 6(b). The sound power is averaged over each row, and the contributions of TIN (dashed lines) and TEN (dotted lines) are shown for each row. For the first row (black lines), TIN and TEN contribute evenly, with TIN dominating at low frequencies and TEN at high frequencies. In subsequent rows, the contribution of TEN decreases significantly due to the reduced wind speed. Although TIN decreases, it does so more slowly than TEN, resulting in a relative

stronger contribution and a greater share of low-frequency content. Notably, both TIN and TEN contributions increase for the third and fourth rows (blue and green lines) compared to the second row (red line), due to the wind speed recovery within the wind farm. For these rows, the TIN contribution (dashed lines) increases slightly faster than the TEN contribution (dotted lines), due to the increased turbulence dissipation rate, which only influences TIN.

Fig. 6(c) presents the corresponding data for the staggered layout. Similarly to the aligned case, the OASWL is very consistent for turbines in the same row. The two first rows present OASWL very close to that of the isolated turbine with a small increase for the second row. This is attributed to the accelerated flow between turbines of the first row (see Fig. 3(c)), causing slightly higher wind speeds at the second row. Furthermore, rows three and four produce considerably more sound than in the aligned case, leading to higher overall noise from the staggered wind farm. As shown in Fig. 4, the flow fields confirm that the last two rows experience similar inflow conditions, which explains their comparable sound production. As a side note, the staggered wind farm also produces more power than the aligned configuration. We do not analyze this here, as it is already well documented in the literature (see, e.g., Stevens and Meneveau [6]).

As expected, the spectra of the first two rows (black and red lines), shown in Fig. 6(d), are almost superimposed, as are those of the last two rows (blue and green lines). Additionally, like in the aligned layout, low-frequency content becomes more prominent in the last two rows because of the increased TIN contribution.

4.3. ΔL and propagation effects

In this section the effect of the flow on propagation is studied by considering the ΔL obtained from the WAPE simulation for a single point source at hub height.

4.3.1. Single wake

Fig. 7(a) illustrates the ΔL for an isolated turbine at a 1 kHz third-octave center frequency. Refraction driven by the mean flow gradient induces several distinct features, including an upwind shadow zone originating at $x = -200$ m and a downwind wake focusing effect that yields ground-level amplification at $x = 2$ km. From this initial focal point shown in Fig. 7(a), the ΔL increase moves away from the downwind propagation direction as the source-receiver distance grows, forming a characteristic “V” shape. Increased propagation angles weaken this wake focusing and shift its ground intersection further downstream; as seen in Fig. 7(c) compared to Fig. 7(b).

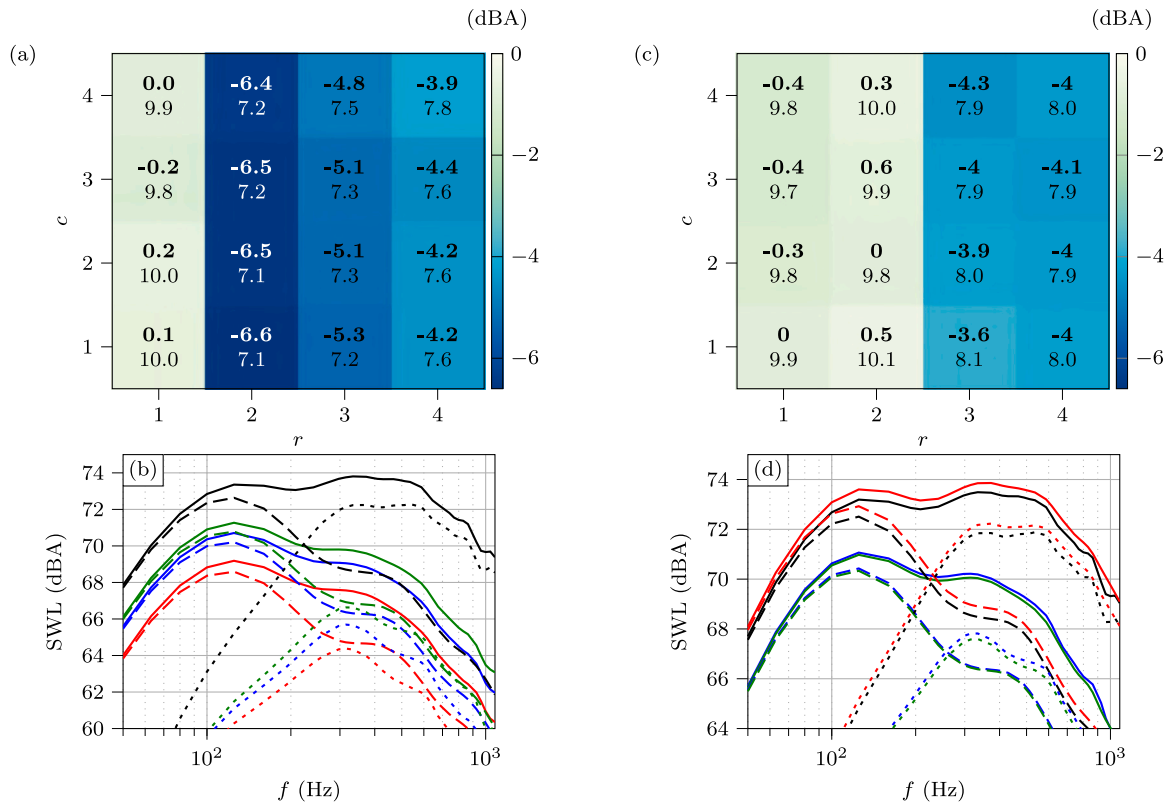


Fig. 6. OASWL (in bold) relative to the isolated case for each turbine of the (a) aligned and (c) staggered wind farms. The rotational speed Ω in rpm for each turbine is indicated below. SWL spectra averaged over each column of (b) the aligned and (d) staggered wind farms. Solid lines show the total SWL, dashed and dotted lines show the TIN and TEN contribution, respectively. The first, second, third and fourth rows are shown in black, red, blue and green, respectively.

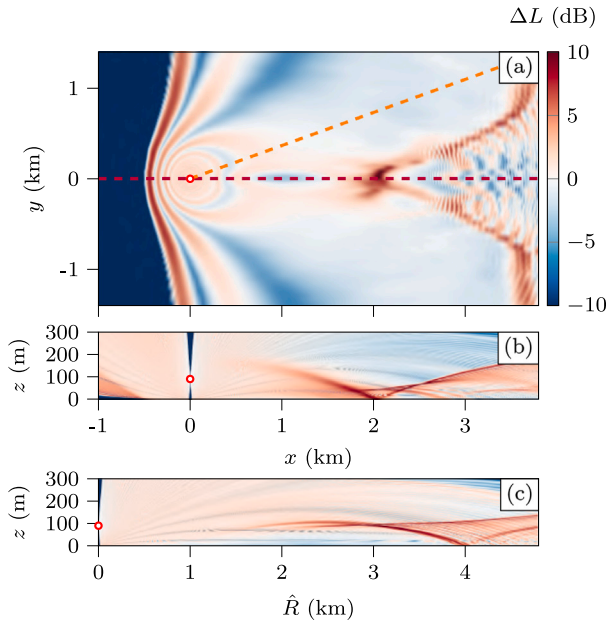


Fig. 7. ΔL at $f_c = 1$ kHz for a source located at hub height of the wind turbine (red dot) for an isolated turbine in the plane (a) $z = 2$ m, (b) $y = 0$ m (dashed purple line), and (c) $\tau = 20^\circ$ (dashed orange line). \hat{R} is the radial distance from the turbine.

4.3.2. Multiple wakes

The ΔL fields corresponding to the four turbines positioned in the first column ($c = 1$), are depicted for the aligned and staggered cases in

Fig. 8. The ΔL from each turbine are shown separately to investigate the propagation effects arising for each row. For the first two rows, wake interactions significantly affect the sound focusing pattern, resulting in two distinct focal regions emerging from the bottom and top of the wake. Compared to the single turbine case (Fig. 7(b)) the focusing is much stronger due to a channeling effect of the wind farm. This focusing reaches the ground slightly closer to the source for the aligned case (at $x = 1.8$ km) compared to the staggered case (around $x = 2.1$ km). However, overall, the difference in flow patterns has a limited influence on the sound propagation from the first turbine row. The same holds for the second row where stronger focusing is observed compared to the single-turbine case.

In contrast, for the turbines in the last two rows, focusing is less efficient than for the single turbine case. This can be explained as the wind speed gradients behind the wind farm are smaller than those created by a single turbine. Upwind of the first row the shadow zone appears to be identical to the single turbine case in Fig. 7. For the subsequent rows, due to the wakes of the upstream turbines, the shadow zone is pushed back toward the front of the wind farm.

The wind farm flow influences sound propagation in all directions. To showcase this, the ΔL is plotted for the propagation plane $\tau = 20^\circ$ in Fig. 9. For this propagation direction there is a clear difference between the single turbine (Fig. 7(c)), the aligned and the staggered wind farm. The presence of other wakes in this direction creates another focusing for the first two turbines in the aligned case, see Figs. 9(a, b). It reaches the ground about 2.5 km downwind of the wind turbine. For the turbines of the third and fourth rows the velocity gradients are not strong enough to create focusing, see Figs. 9(c, d). In the staggered layout, a strong focusing is observed for the first three rows, Figs. 9(e-g). This is explained by observing the projected flow fields, see the contour lines. Due to the staggered layout, this propagation plane crosses more wakes in the staggered case than in the aligned case.

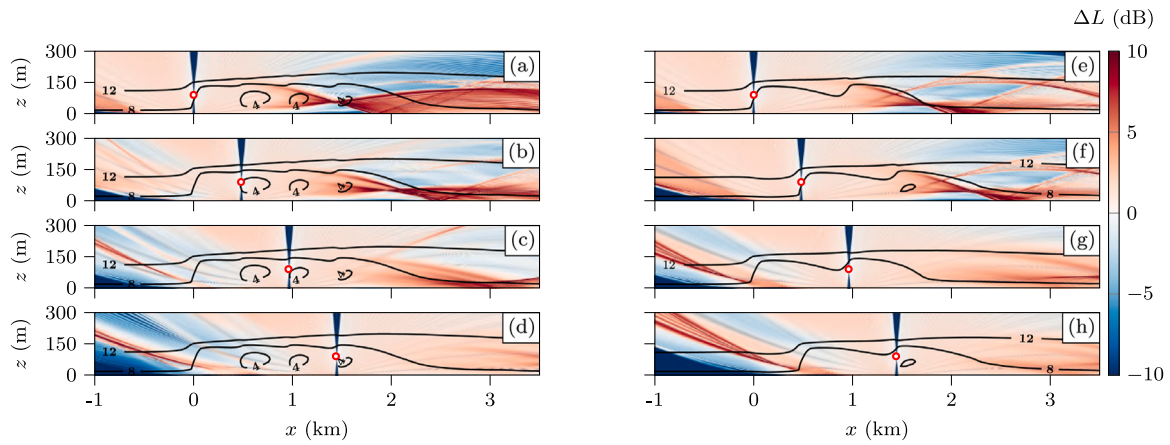


Fig. 8. ΔL at $f_c = 1$ kHz for a source located at hub height of the wind turbine (red dot) in the first column and for the plane $y = 720$ m. The propagation is shown for each row (top to bottom) and for the aligned (left) and staggered (right) cases. The streamwise wind speed contour is shown black lines.

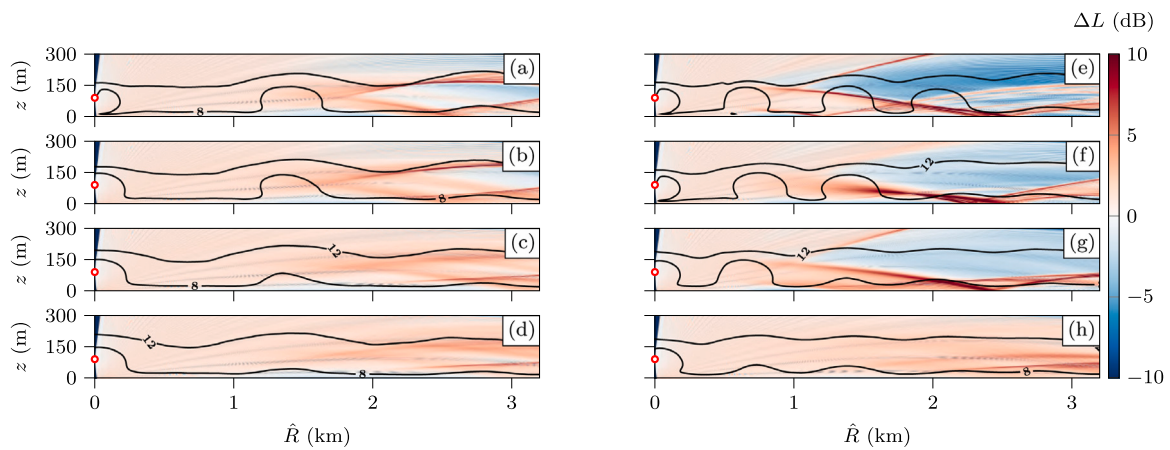


Fig. 9. ΔL at $f_c = 1$ kHz for a source located at hub height of the wind turbine (red dot) in the first column and for the plane $\tau = 20^\circ$. The propagation is shown for each row (top to bottom) and for the aligned (left) and staggered (right) cases. \hat{R} is the radial distance from the turbine. The wind speed projected in the propagation plane is shown with the black contour lines.

This induces multiple sound wave focusing zones, resulting in a strong increase in ΔL at the ground at $R = 2.5$ km. From this observation we can expect a higher SPL and AM in these propagation directions compared to the single turbine or aligned wind farm.

4.4. OASPL and AM

4.4.1. Single turbines

Fig. 10 shows the OASPL and the AM at $z = 2$ m for the isolated wind turbine. This baseline case presents different features characteristic of wind turbine noise propagation. The dipolar shape induced by the TIN and TEN directivity is visible in Fig. 10(a), displaying the characteristic cross-wind extinction zone. A shadow region is also present upwind for $x < -300$ m. It is created by the negative effective sound speed gradient in the upwind propagation direction. Finally, some focusing patterns are visible downwind, which can be attributed to the wake and ABL shear. The “V” shape that was already visible in the ΔL fields (see Section 4.3) is still present. Note that, in rural environments, background noise typically averages 30 dBA; consequently, wind turbine emissions below this threshold often remain imperceptible. Nevertheless, the analysis of propagation effects and inter-case comparisons is performed for OASPL below this value to yield fundamental insights into acoustic transmission and relative turbine positioning. These findings remain relevant for larger turbines or diverse atmospheric conditions where operational noise levels may increase significantly.

As previously stated, AM is essential in assessing perception of wind turbine noise. Fig. 10(b) shows the AM measured at 2 m height, highlighting cross-wind AM caused by the rotating blades moving toward and away from the receiver. Consistent with Oerlemans and Schepers [33], we find that there is an asymmetry in AM cross-wind, the higher AM values are observed for the negative y positions which corresponds to the observer close to the downward moving blade. AM also increases in the upwind direction due to the negative wind speed gradient, similarly to the observation of Mascarenhas et al. [34]. The change in source height due to blade rotation alters the focusing pattern, leading to AM at the ground, visible downwind for $x > 1.5$ km. This increase in AM directly induced by the wake effect is consistent with the work of other authors [4,35].

To further study the impact of multiple wakes on sound propagation, Fig. 11 shows the averaged OASPL at 2 m for one turbine in each row of the aligned and the staggered cases. The effect of the additional wakes on sound propagation is visible both for the staggered and aligned layouts. For the aligned case, Figs. 11(a-d), areas of noise amplification and noise reduction are present at almost constant y values. The wakes of the first, third and fourth columns are responsible for these patterns by focusing the sound wave in some specific regions. These patterns are mostly visible for the two first turbines and are less present for the last turbine. This is consistent with the ΔL results shown in the previous section. For the staggered case, see Figs. 11(e-h), the focusing pattern appears less symmetrical which can be explained by the turbine arrangement, which leads to more complex wake physics

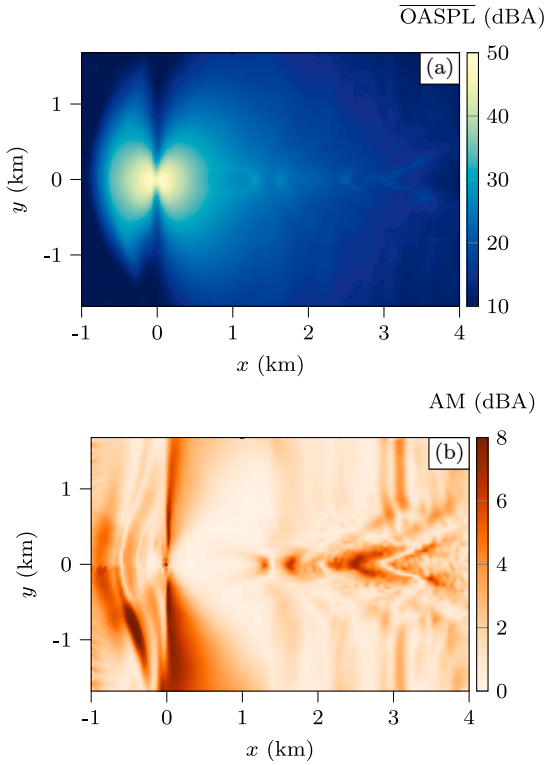


Fig. 10. (a) $\overline{\text{OASPL}}$, (b) AM at $z = 2$ m for an isolated turbine.

in the wind farm. Focusing also appears more efficient for the first two rows, which again is in agreement with observations on ΔL .

The wind farm flow also modifies the AM pattern as demonstrated in Fig. 12. In the aligned case the AM increases strongly in the downwind direction for the first two rows, see Figs. 12(a) and (b). Due to the wake superposition, focusing is more efficient, which leads to significant variations in OASPL as the blade rotates. For the last turbine, Fig. 12(d), no AM increase is visible downwind. As shown in the previous section, focusing is less efficient for the last row, leading to reduced AM. The first row in Fig. 12(a) presents similar crosswind AM as the isolated turbine, see Fig. 10(b). Crosswind AM is reduced for all the subsequent rows due to reduced rotational speed and hence less convective amplification effect. Finally, the first row shows upwind AM similar to the single-turbine case, as the flow is similar in both cases. For the subsequent rows the upwind AM pattern is modified by the wakes upwind of the turbine. However, the AM increase is mostly present inside the wind farm and hence is not particularly relevant.

For the staggered layout, Figs. 12(e) and (f) show a downwind increase in AM for the first two rows. Additionally, significant AM increase is also visible for other propagation angles ($|\tau| < 90^\circ$). This supports the ΔL results which shows enhanced focusing for $\tau = 20^\circ$ compared to the aligned case. Figs. 12(g) and (h) display no direct downwind AM for the third and fourth rows, but an increase in AM for the third row is visible for $\tau = 20^\circ$ and $\tau = -20^\circ$. This is again in agreement with our ΔL results. Crosswind AM is similar for the first two rows, as shown in Figs. 12(e) and (f), which is expected given their nearly identical source emission. The crosswind AM for the last two rows are lower, see Figs. 12(g) and (h). The upwind AM for the first row is similar to that in the aligned wind farm and the single-turbine case. In contrast, the upwind AM for turbines in rows 2-4 are influenced by the flow within the wind farm.

4.4.2. Full wind farm

Figs. 13(a) and (b) display the $\overline{\text{OASPL}}$ fields at 2 m, considering the contribution of 16 wind turbines. In the aligned case, each turbine's

distinct contributions are visible, with the first row emitting higher sound levels. Upwind, a shadow zone starts at $x = -500$ m, while downwind, the focusing patterns seen in the single turbine case are absent, as expected due to the weak focusing from the last row's wakes and the averaging effect of multiple turbines. Cross-wind extinction zones ($y < -720$ m and $y > 720$ m) are significantly attenuated for the second ($x = 480$ m), third ($x = 960$ m), and fourth ($x = 1.44$ km) rows due to upwind turbines' contributions. The first row ($x=0$) shows two cross-wind extinction zones, explained by the low sound power level from the second row's turbines (Section 4.2) and upward refraction reducing noise contribution of the downwind turbines. The staggered layout OASPL field differs from the aligned layout, with higher OASPL near the wind turbine for the second row and slight focusing patterns downwind at around $x = 2.5$ km.

Fig. 13(c) shows the AM field for the aligned layout. Compared to the isolated case only crosswind AM for the first row and upwind AM are present in the aligned case. The downwind AM generated by individual turbine wakes, which appeared more pronounced when viewed separately, is not visible in the total field. This is explained by a smoothing of the amplification due to the contribution of multiple turbines. As previously stated the AM cross wind for the first row is still visible because the contribution of the subsequent rows is very low in this region. Similarly, the upwind AM has a comparable amplitude to that of the isolated turbine.

For the staggered layout, Fig. 13(d), there is a significant increase in AM downwind ($2 < x < 2.5$ km) compared to the aligned case. In this case, AM increases for turbines in the first and second rows across multiple propagation directions. Additionally, the last rows emit more noise, contributing to higher AM levels downstream. The location of increased AM downwind in Fig. 13(d) aligns with the AM rise observed for the first and second rows in Figs. 12(e) and (g). This leads to think that the first and second rows are responsible for the increased AM downwind. Upwind and crosswind, AM are similar to that of the aligned case.

To further investigate the differences between the aligned and staggered layouts, Fig. 14 compares the $\overline{\text{OASPL}}$ and AM, averaged over $|y| < 720$ m, for the aligned and staggered layouts. Upwind both configurations show similar results. However, downwind of the wind farm ($x > 2$ km), the staggered case demonstrates a significant increase of 3 dBA in $\overline{\text{OASPL}}$. This increase is partially attributed to an approximate 1.5 dBA rise in individual turbine sound emission, determined by computing total wind farm noise in free field, with the remaining discrepancy resulting from layout-induced propagation effects. Another significant feature is the increase in AM at around $x = 2.5$ km, see Fig. 14(b). The maximum downwind AM is 1 dBA for the aligned layout and 2 dBA for the staggered layout, which is usually considered as a threshold for perceiving AM [30].

4.5. Wind farm flow effect on sound propagation

To further assess the effect of the wind farm flow physics on sound propagation, the $\overline{\text{OASPL}}$ from the wind farm is computed using the ΔL computed for the single turbine case. This enables the computation of wind farm sound propagation using realistic sound power levels, but without sound refraction induced by the wake interaction. This artificial case is then subtracted from the real wind farm case to obtain

$$\Delta \overline{\text{OASPL}} = \overline{\text{OASPL}}_{16T}^{\text{tot}} - \overline{\text{OASPL}}_{1T}^{\text{tot}} \quad (5)$$

where $\overline{\text{OASPL}}_{16T}^{\text{tot}}$ and $\overline{\text{OASPL}}_{1T}^{\text{tot}}$ are the total fields obtained by integrating over all frequencies and by logarithmically summing the contribution from each turbine (t_r^c), obtained with

$$\text{SPL}_{16T}(t_r^c) = \text{SWL}(t_r^c) + \Delta L(t_r^c) - \alpha R - 10 \log_{10}(4\pi R^2) \quad (6)$$

$$\text{SPL}_{1T}(t_r^c) = \text{SWL}(t_r^c) + \Delta L_{1T} - \alpha R - 10 \log_{10}(4\pi R^2)$$

where $\text{SWL}(t_r^c)$ is the sound power obtained for each turbine, $\Delta L(t_r^c)$ is the sound pressure level relative to the free field of each turbine in the

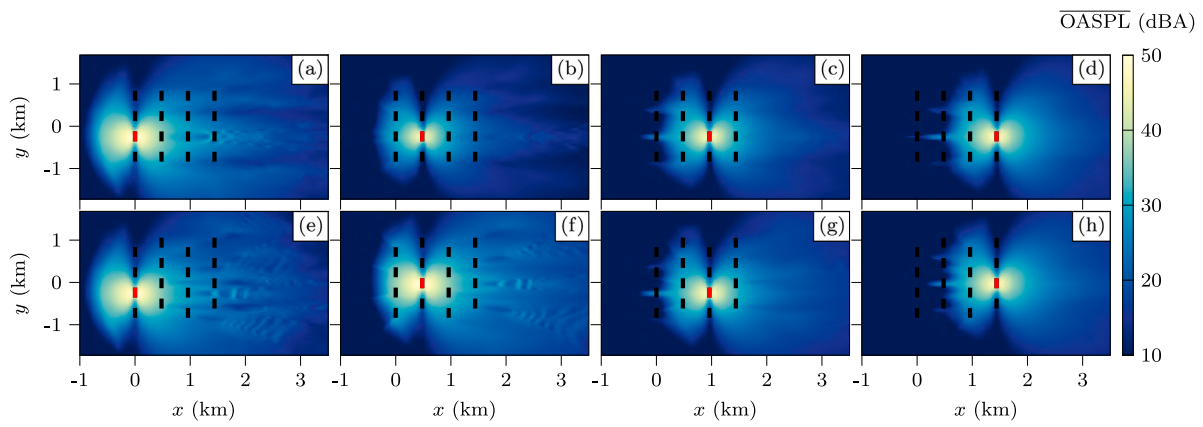


Fig. 11. Contribution of a single turbine (in red) to the $\overline{\text{OASPL}}$ at $z = 2$ m, Figs. (a) to (d) correspond to the aligned layout and Figs. (e) to (h) to the staggered layout. Wind turbine rotors are indicated with black lines.

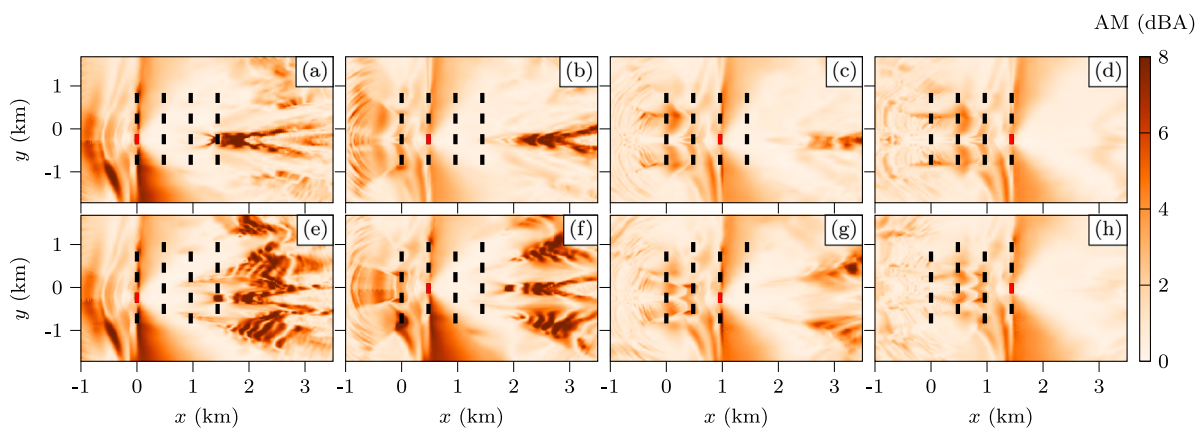


Fig. 12. Amplitude modulation generated by a single turbine (in red) at $z = 2$ m, Figs. (a) to (d) correspond to the aligned layout and Figs. (e) to (h) to the staggered layout. Wind turbine rotors are indicated with black lines.

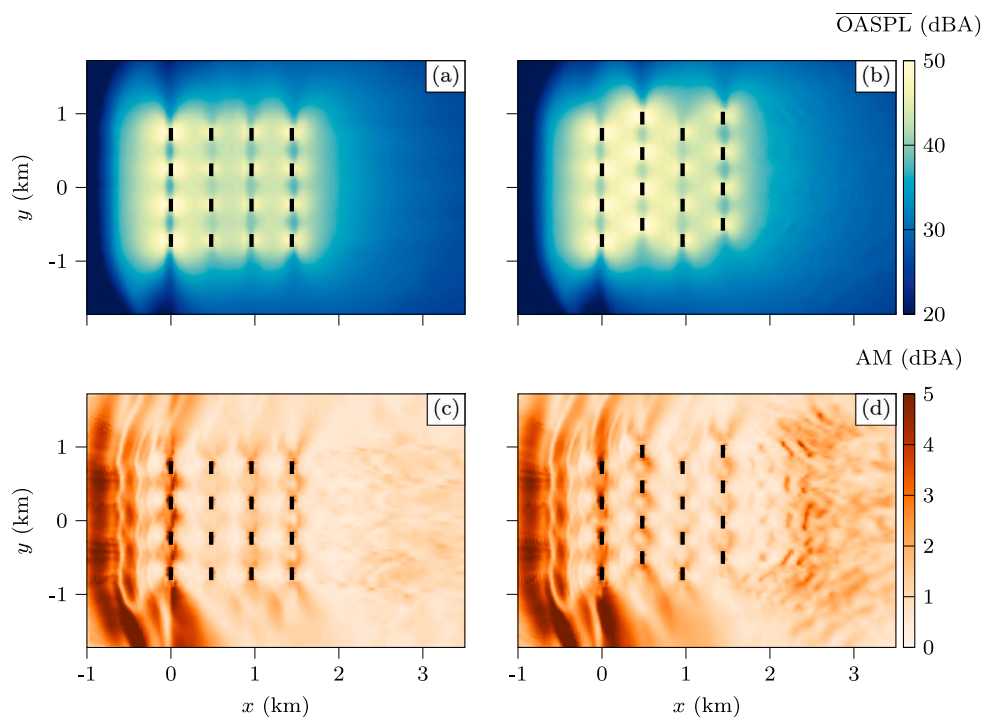


Fig. 13. (a), (b) $\overline{\text{OASPL}}$ and (c), (d) AM for the (a), (c) aligned and (b), (d) staggered layouts at $z = 2$ m. Wind turbine rotors are indicated with black lines.

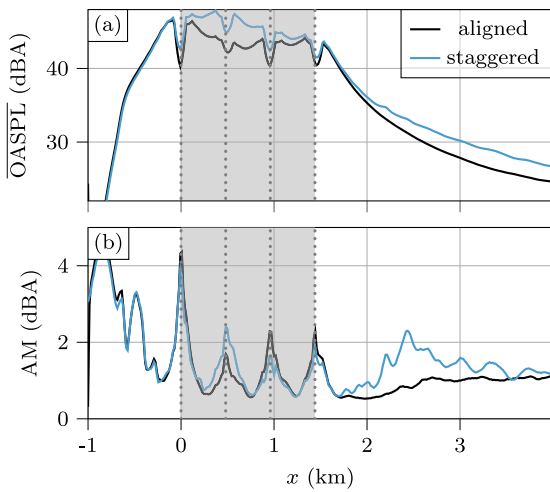


Fig. 14. Spatially averaged (a) $\overline{\text{OASPL}}$ and (b) AM for the aligned and staggered layouts for receivers at $z = 2$ m. The $\overline{\text{OASPL}}$ and AM values are averaged over $|y| < 720$ m. Wind turbines' positions are indicated with gray dotted lines, the gray area represents the positions inside the wind farm.

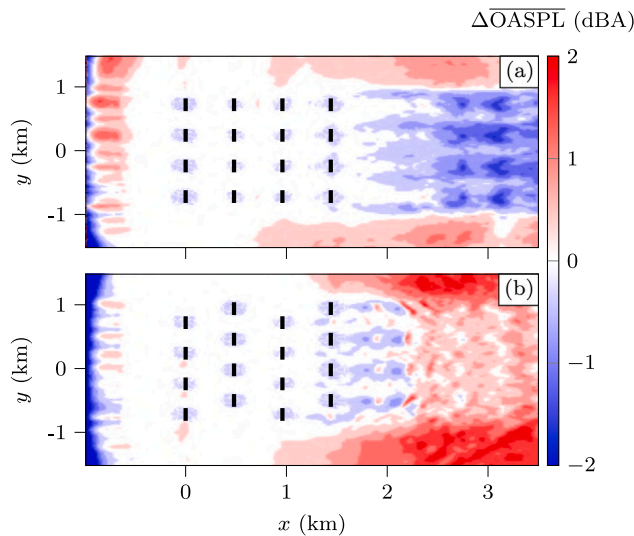


Fig. 15. In the (a) aligned and (b) staggered cases, difference between the $\overline{\text{OASPL}}$ obtained with the full wind farm flows and without accounting for flow interactions between turbines.

wind farm, and ΔL_{1T} is the sound pressure level relative to the free field corresponding to the single turbine case. Note that the actual procedure is a bit more complex because we use different ΔL according to the blade position. But the general idea is that between both computations only the propagation effect is modified.

Fig. 15 shows the corresponding impact of realistic wind farm flow physics on sound propagation at 2 m height. Inside the wind farms, the difference is close to 0 indicating a minimal impact of the flow. However, downstream, significant differences are observed. Directly downwind of the aligned wind farm, see Fig. 15(a), for $|y| < 720$ m, the $\overline{\text{OASPL}}$ is between 1 dBA and 2 dBA lower when accounting for the realistic wind farm flow. On the contrary, outside the direct downwind direction ($|y| > 720$ m) an increase is observed due to the combined wake effect. As shown in the previous section, multiple wakes can create focusing outside the downwind direction, which is not present if only a single wake is considered. Upwind there is an increase when considering the realistic wind farm flow. Note that this increase inside the shadow zone is not significant, and that it can be explained by the

fact that the shadow zones of the second, third and fourth rows are pushed back due to the auxiliary wakes.

The effect of the staggered wind farm flow on propagation is shown in Fig. 15(b). Here an even stronger effect than for the aligned case is visible. Note that only propagation effects can cause differences in $\overline{\text{OASPL}}$. Consequently, the staggered layout has a strong impact on downwind propagation, resulting in a general increase in sound levels. In comparison, for the aligned case, there was a decrease directly downwind of the wind farm and an increase outside the direct downwind direction. This confirms that the staggered case is indeed a worst case scenario for acoustics due to both an increase in sound emitted by the turbines and propagation effects that tend to increase the $\overline{\text{OASPL}}$ downwind.

4.6. Beating effect

Finally, it is important to note that turbines in a wind farm rotate at different speeds. As a result, signals with slightly different periods add up and a beating effect can be observed at certain locations, as described by van den Berg [36]. This effect occurs when turbine contributions have similar magnitudes and their rotational speeds are close, producing a signal modulated by a low-frequency envelope relative to the blade-passing frequency. Fig. 16 shows the OASPL signals at four receiver locations for the aligned and staggered wind farm layouts.

Figs. 16(a, b) correspond to upwind receivers, while Figs. 16(c, d) show downwind positions. Beating is evident at both upwind locations in both layouts, with AM levels ranging from approximately 4 dBA to below 2 dBA, exceeding the perception threshold reported by Nguyen et al. [30]. Downwind of the aligned wind farm, AM levels are very low. In contrast, behind the staggered wind farm, a weaker beating effect remains visible. The presence of multiple turbines likely smooths the signal, reducing the modulation depth. This beating adds an extra layer of variability, as AM itself is intermittent and sometimes perceptible. Intermittent sounds tend to be more noticeable than continuous ones, especially when they stand out from background noise [37].

5. Discussion and conclusion

This study investigated the influence of wind farm layout and flow physics on noise generation and propagation, using large-eddy simulations coupled with acoustic modeling. Two wind farm configurations, aligned and staggered, were analyzed, with an isolated turbine case serving as a baseline. The results for overall sound pressure level and amplitude modulation in the reference case aligned with earlier findings by Barlas et al. [38] and Heimann and Englberger [3].

The wind farm layout has a clear effect on both the overall noise levels and the way sound propagates downwind, consistent with earlier work by Sun et al. [8]. In aligned layouts, strong wake effects lead to more variation in noise production across turbine rows. In the first row, turbulent inflow noise and trailing-edge noise contribute about equally overall. Turbulent inflow noise dominates at low frequencies, whereas trailing-edge noise dominates at higher frequencies. Farther downstream, trailing-edge noise decreases because wind speeds are lower, while turbulent inflow noise remains relatively high because turbulence levels are higher. Staggered layouts result in higher overall noise levels, as turbines experience stronger inflow and less variation in turbulence dissipation rate inside the farm.

The physics of wind farm flow also significantly affect sound propagation with additional focusing occurring downwind compared to an isolated case due to the wakes of the other turbines in the farm. This aligns with the findings of Sun et al. [8] who showed similar effects when considering wake superposition. Nyborg et al. [11] also demonstrated that wind farm flow has an influence on the noise level and hence should be accounted for when implementing curtailment plans. The staggered layout presents enhanced focusing downwind leading to increase noise level and amplitude modulation. We also showed that

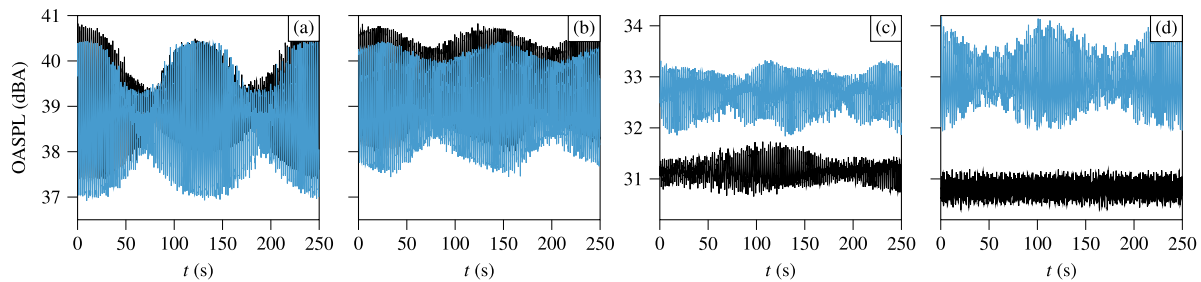


Fig. 16. OASPL time signal at four receiver locations in the aligned (black) and staggered (blue) wind farms. Figures (a) $(x, y) = (-500, 0)$ m and (b) $(x, y) = (-500, 240)$ m correspond to upwind receivers and Figures (c) $(x, y) = (2500, 0)$ m and (d) $(x, y) = (2500, 240)$ m to downwind receivers.

these effects were not reproducible without accounting for the multiple wake interaction hence underscoring the importance of capturing full wind farm flow physics when predicting acoustic impact. The high computational cost of the methods does not allow for further parameter analysis. However, general trends can be derived from previous work and our observations. Larger wind turbines should yield higher noise source level with lower frequency content which could also lead to increase downwind amplitude modulation. While increased streamwise turbine spacing facilitates wake recovery and yields higher noise levels for downstream turbines, its definitive impact on downwind amplitude modulation remains unclear and should be further investigated. Increased spanwise spacing between turbines reduces the influence of lateral wakes on refraction patterns, thereby reducing downwind focusing effects.

As previously stated we considered time-averaged flow field from a stable boundary layer condition, that represents a worst case scenario for downwind noise annoyance due to maximized focusing effects. Incorporating unsteady flow fields or neutral to unstable atmospheric conditions would likely diminish focusing efficiency through smaller wakes and reduced wind speed gradient. However it may simultaneously increase AM due to additional turbulence fluctuation impacting the source level and atmospheric refraction. While these phenomena have been documented for single turbines [3,38], their impact on large wind farm requires further investigation. Finally, transitioning from academic case toward real wind farm would allow to apply this methodology to further analyze the influence of atmospheric conditions on observed noise level and amplitude modulation [13,30]. Overall, the findings support the need to include realistic flow fields in acoustic models and provide a foundation for more accurate noise impact assessments, which are essential for wind farm design, permitting, and public acceptance.

CRediT authorship contribution statement

Jules Colas: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Ariane Emmanuelli:** Writing – review & editing, Validation, Supervision, Methodology, Investigation, Formal analysis, Conceptualization. **Didier Dragna:** Writing – review & editing, Validation, Supervision, Methodology, Investigation, Conceptualization. **Richard J.A.M. Stevens:** Writing – review & editing, Validation, Supervision, Methodology, Investigation, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Richard Stevens reports financial support was provided by European Research Council. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Reported data can be made available to the reader upon request to the authors.

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