The wind effect on sound propagation over urban areas: Predictions for generic urban sections

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\section*{ABSTRACT}

The effect of a downward refracting atmosphere on distant sound propagation over various generic urban areas is predicted. The work uses a two-step approach, by first computing the wind field with computational fluid dynamics (RANS-CFD), and then adopting the mean wind field in a computational acoustics (PSTD-CA) method. These approaches were found to be valid for the studied geometries. For an urban configuration with multiple building blocks, a sound source is located in a street canyon, representing road traffic, and receivers are located at a distance up to 500 m. From results of calculations for various urban configurations, it can be concluded that: the sound levels increase due to the presence of a downward refracting atmosphere, and this effect is larger for higher frequencies; the wind effect ranges from 15 to 23 dB(A); the urban topology close to the source and receiver can largely influence the wind effect; whereas vegetated roofs have the potential to reduce sound levels without wind, in a downward refracting atmosphere the broadband effect is small (<2 dB(A)), however, a potential for reducing noise levels by roofs with low-frequency sound absorption has been identified.

1. Introduction

In cities, the sound levels caused by noise from surface transport is often determined by nearby traffic. For locations shielded from direct exposure to noise from surface transport, the influence of distant noise sources becomes important [1]. The contribution of sound from distant sources might prevent such areas to be classified as a quiet area [2].

Distant noise sources may become audible under certain meteorological conditions only. Such conditions typically occur in the nocturnal boundary layer, i.e. when a positive temperature gradient is present in the surface layer of the atmospheric boundary layer, and under downwind conditions, i.e. when the mean wind velocity component in the direction from sound source to receiver location of interest is significant. For these conditions, sound waves are refracted downwards and can significantly increase noise levels, see Ref. [3] for a detailed explanation of these phenomena. Another mechanism that increases the sound level due to distant sources is scattering of sound by atmospheric turbulence. This effect is mostly occurring when sound waves are refracted upwards, i.e. when acoustic shadow zones are created, while the sound levels caused by downward refraction are potentially higher than those caused by scattering due to turbulence.

Whereas engineering methods, developed to produce noise maps as mandatory in the European Union (directive 2002/49/EC) account for the effect of meteorological conditions, it is questionable whether the estimation of meteorological effects in these models is sufficient. Indeed, it has been shown that the prediction of meteorological conditions in engineering methods can be improved [4]. A reason for this uncertainty is the lack of data, both from predictions and from measurement data, on the effect of meteorology on sound propagation for various urban scenarios. In particular, data for urban areas are very scarce. Such data would enable an improved accuracy when including meteorological effects in engineering methods.

The prediction of noise levels in urban areas from distant traffic for arbitrary meteorological conditions is not straightforward. First, the spatially dependent temperature and wind field should be predicted. Due to the urban morphology, these fields can for most cases not be predicted analytically; therefore, computational fluid dynamics (CFD) models are needed [5]. To predict acoustic propagation, the influence of meteorology as well as the effect of the urban morphology (with its boundary conditions, multiple reflections and edge diffraction) should be included. This implies that advanced computational acoustics (CA) methods are needed as well for accurately predicting sound propagation.

Previous literature indicates the potential large meteorological
effects on sound propagation, and demonstrates that detailed predictions with CFD and CA are possible.

In an attempt to solve complex urban configurations in the presence of a wind field, Van Renterghem et al. [6] first presented a hybrid computational approach, combining the finite-difference time-domain (FDTD) method and parabolic equation (PE) method, and later applied this to compute the effect of sound propagation from one street canyon to another street canyon, in the presence of a wind field as computed by a Reynolds-averaged Navier-Stokes (RANS) CFD simulation [7]. The study focused on the geometrical details inside the street canyons, with a flat roof between the streets. The wind effect was found to increase with distance between the canyons and to be very significant with respect to the obtained sound pressure level. A numerical study by Schiﬀ et al. [8] using the PE method revealed for the first time the effect of multiple street canyons when sound propagates over it, reporting a frequency independent reduction per street canyon. The wind effect was touched upon, but only for source and receiver located at the roof level [8]. The importance of the roof type for a single building was studied, both regarding the effect of roof shape [9] and the effect of rigid and vegetated roofs [10–12].

The first three-dimensional results of the wind effect on sound propagation over a realistic building were presented by Heimann [13], while still being limited to a maximum frequency of 250 Hz. In more recent studies, the wind effect on urban sound propagation was quantiﬁed in 3D as well [14,15]. While these latter studies are impressive in terms of computational efforts, further modelling efforts are needed to get a better picture of the wind effects for more generic urban topologies. Besides the computational studies, Van Renterghem and Botteldooren carried out measurements at short urban distances [16].

A lack in the current body of literature is the quantification of meteorological effects on distant sound propagation over generic urban areas. Given the fact that a multitude of urban topologies can be deﬁned, as well as various properties of ground and roof surfaces, and meteorological conditions, this paper aims to quantify the wind effect on urban sound propagation for a range of generic urban conﬁgurations by means of numerical calculations. A potential extension of this work could be a study of optimizing natural ventilation of buildings, which both relies on wind as the driving force of ventilation and noise exposure on the façade.

The approach taken in this paper is to ﬁrst compute the urban wind ﬂow ﬁeld using an appropriate CFD approach, and then use this wind ﬂow ﬁeld to compute sound propagation in detail using a CA approach with the wave-based pseudospectral time domain (PSTD) method. The distances from source to receiver are up to 500 m in this work, and the sound source and receiver position are separated by multiple building blocks. Variations are implemented through varying roof heights and street widths, roof parapets and vegetated roofs. This initial study is limited to one reference mean wind velocity and excludes the effect of temperature gradients and turbulence on sound propagation.

In section 2, the calculation approaches for the wind ﬂow ﬁeld and sound propagation are presented. Also, the processing of the results is described. Section 3 introduces the various urban conﬁgurations studied. The appropriateness of the used CFD and CA techniques as well as results from applying these techniques for the chosen urban conﬁgurations are shown in Section 4 and discussed in Section 5. Finally, conclusions and suggestions for further work can be found in Section 6.

2. Methodology

2.1. Modelling approach

Meteorological effects on sound propagation are in this paper limited to the mean wind effect. For the conﬁgurations of interest, both for the wind ﬂow calculation as for the sound propagation calculation, analytical solutions do not exist. Therefore, a two step calculation approach is adopted here by numerically solving the governing equations of interest, which has been done previously, e.g. Refs. [13,14,17–19]. First, the mean wind ﬁeld is computed for the urban conﬁguration of interest (see Section 3 for the conﬁgurations of interest) by solving the incompressible steady RANS equations. Then, to compute sound propagation in the urban conﬁguration of interest, the mean wind ﬁeld is used in the governing compressible linearized ﬂuid dynamics equations for sound propagation.

2.2. Wind ﬂow modelling

CFD is used to predict the mean wind ﬁeld for the different urban conﬁgurations. The RANS approach is chosen and the commercial CFD software ANSYS Fluent is used [20]. Although Large Eddy Simulation (LES) intrinsically can provide more accurate results than RANS, the RANS approach is still widely used in wind engineering and urban physics [21–29]. It combines a relatively low computational cost with good results for a range of ﬂow problems. The RANS equations only resolve the mean ﬂow, while all scales of turbulence are modelled (approximated) using a turbulence model. The realizable k-ε turbulence model [30] is employed in this study, which is a two-equation eddy-viscosity turbulence model that solves two additional transport equations, one for the turbulent kinetic energy k and one for turbulent dissipation rate ε. This approach is known to be approximate for spatial regions where inhomogeneous turbulent structures prevail, but has also been shown to be able to provide accurate results for a range of wind engineering ﬂow problems (e.g. Ref. [21]).

2.3. Sound propagation modelling

Sound propagation in the studied urban conﬁgurations is modelled by solving the linearized Euler equations (LEE) for the acoustic pressure and velocity components:

$$\frac{\partial \mathbf{u}}{\partial t} = - (\mathbf{u} \cdot \nabla) \mathbf{u} - (\nu \mathbf{V}) \mathbf{u} - \frac{1}{\rho_0} \nabla p,$$

$$\frac{\partial p}{\partial t} = - \mathbf{u} \cdot \nabla p - \rho_0 \mathbf{c}^2 \mathbf{V} \cdot \mathbf{u},$$

with c the speed of sound, ρ0 the mean density, u0 the mean wind velocity vector, u and p the acoustic velocity and pressure, respectively, with the components of the velocity denoted by $\mathbf{u} = [u, v, w]^T$. The spatially dependent wind components u0 are adopted from the results of the CFD calculations.

A simplified way to include the effect of the mean wind component is by solving the linear acoustics equations with the effective sound speed approach

$$\frac{\partial \mathbf{u}}{\partial t} = - \frac{1}{\rho_0} \nabla p,$$

$$\frac{\partial p}{\partial t} = -\rho_0 c_{eff}^2 \nabla \cdot \mathbf{u},$$

with $c_{eff} = c + u_0$ the effective sound speed, i.e. the horizontal mean wind component added to the sound speed. This effective sound speed approach is commonly adopted for atmospheric sound propagation modelling, where horizontal propagation distances are much larger than the vertical distances and horizontal wind speed components dominate [3]. For conﬁgurations where vertical velocity components are signiﬁcantly inﬂuencing sound propagation, LEE (Eq. (2)) should be used.

Equations (2) and (3) are solved by the PSTD method [31]. This is a volume discretization method using a Cartesian grid. In PSTD, spatial derivatives are solved by the Fourier pseudospectral method, implying that only two spatial points per wavelength are needed for a propagation medium that is homogeneous and at rest. The equations are marched in time by a low-storage optimised 6-stage Runge-Kutta method.
The method has been validated for atmospheric sound propagation in the presence of staircase-type boundaries and in the presence of a mean wind velocity component [31]. The accuracy of PSTD for urban applications was found to be related to a grid size with about 2.1 grid cells per shortest acoustic wavelength. For scenarios with wind, this upper frequency can be scaled down from the maximum mean wind velocity [31]. A limitation of PSTD is the treatment of the boundary conditions, as for the ground surface, facades and roofs. It is related to the use of Fourier transforms to compute the spatial derivatives, which require the physical variables to be periodic in space. Whereas developments are ongoing to hybrised the spatial domain by two different numerical methods [32], the PSTD method is able to solve for frequency independent boundary conditions [33]. For the outer domains in outdoor scenarios, a gradually absorbing layer (perfectly matched layer PML) is implemented to prevent sound waves from being reflected into the domain again.

### 2.4. Acoustic quantifiers

The acoustic results of interest here are the relative sound levels in the studied urban configurations. Various relative sound levels are calculated. The first is the relative sound pressure level:

\[
L_{\text{ref}}(x_i) = 10 \log_{10} \left( \frac{P_{C_i}(x_i)}{P_{C_i}^0} \right),
\]

with

\[
P_{C_i}(x_i) = \int F \left[ p(f, x_i) \right] df,
\]

and

\[
|P_{C_i}(x_i)|^2 = \sum_{\ell} |P_{C_i}^{\ell}(f, x_i)|^2,
\]

with \( p(f, x_i) \) the pressure signal as a function of time for configuration \( i \), as computed with the PSTD method, \( p_{C_i}(t) \) is the computed solution for a chosen reference configuration \( C_k \), \( P_{C_i}(f) \) is a solution in free field conditions, and \( x_i \) is the vector of the discrete receiver locations. \( F \) denotes the forward Fourier transform from time to frequency, and equation (6) represents the summation of the acoustic energy per 1/3 octave band \( \ell \). The superscript \( n \) in \( P_{C_i}^{\ell} \) denotes that the pressure field is normalised with respect to the spectrum of the sound source. A definition of (1/3) octave bands with lower and upper frequencies can be found elsewhere [3].

The second level is the wind effect (WE) computed as:

\[
WE_{C_i}(x_i) = 10 \log_{10} \left( \frac{P_{C_i}^{W,1}(x_i)}{P_{C_i}^{W,0}(x_i)} \right),
\]

where subscripts \( C_k \) denotes the reference configuration that represents the configuration without wind and \( C/W \) the configuration with wind (configuration numbers can be found in Table 1). Both quantifiers are computed per receiver position as well as averaged over the receiver positions in the last street canyon. Averaging is done to suppress the fluctuations of the sound pressure level as a function of the receiver position in the last street canyon, and it is computed as follows:

\[
L_{\text{ref}} = 10 \log_{10} \left( \frac{\sum_{\ell} |P_{C_i}^{\ell}(x_i)|^2}{\sum_{\ell} |P_{C_i}^{\ell}(x_i)|^2} \right),
\]

\[
WE_{C_i} = 10 \log_{10} \left( \frac{\sum_{\ell} |P_{C_i}^{W,1}(x_i)|^2}{\sum_{\ell} |P_{C_i}^{W,0}(x_i)|^2} \right),
\]

where the summation runs over the index \( \ell \) for receiver positions in the last street canyon. Finally, broadband results are computed assuming road traffic in the street canyon composed out of 80% lightweight vehicles and 20% heavy duty vehicles, driving at 30 km/h. The Cnossos approach is used to compute the sound power level per octave band [34]. The broadband result is computed as:

\[
L_{\text{ref}, \text{BB}} = 10 \log_{10} \left( \frac{\sum_{\ell} \frac{C_{\text{ref}}(i)^2}{10^L_{C_i}^{\ell,0}}}{\sum_{\ell} 10^{L_{C_i}^{\ell,0}/10}} \right),
\]

where the \( L_{C_i}^{\ell,0} \) are the sound pressure levels computed with the Cnossos model for the same source-receiver distance as \( L_{C_i}^{\ell} \), but for a scenario without buildings. The third octave band sound power levels used to compute \( L_{C_i}^{\ell,0} \) are obtained from Ref. [34] by subtracting 10log(3) dB from the octave band power levels. \( L_{C_i}^{\ell} \) is used here as this is the level relative to the scenario without canyons. Finally, the broadband wind effect is computed by subtracting \( L_{C_i}^{\ell} \) for scenarios with and without wind.

### 3. Computational models and settings

#### 3.1. Urban scenarios

In order to investigate the influence of a downward refracting atmosphere on sound propagation over an urban configuration, a typical urban geometry is chosen (Figs. 1–3). It needs to be emphasised that this is a first investigation with results valid for the chosen configurations.

A two-dimensional configuration is chosen, as this allows for calculating at distances of 500 m within a reasonable calculation time for frequencies up to the 1600 Hz 1/3 octave band, which is a sufficiently high octave band considering distant urban road traffic noise at low vehicle speeds in shielded urban locations [8]. The justification for the two-dimensional calculations is based on the fact that the scenarios can be considered as long streets in the third dimension (see Fig. 2) and that the sound source is to be regarded as a coherent line source. The propagation paths of interest here are in the cross sections considered. Lateral propagation paths are not of interest here as wind effects are less significant for those paths. This would also be the case if the geometry of the considered scenarios changes in the third dimension. Furthermore, it has been shown that the effect of shielding sound by barriers (like building blocks) is similar in two and three dimensions.

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Basic scenario</th>
<th>Canyon widths (m)</th>
<th>Wind</th>
<th>Roof</th>
<th>Vegetated roof</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>no</td>
<td>–</td>
<td>no</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>C1</td>
<td>ERH</td>
<td>20</td>
<td>no</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>C1W</td>
<td>ERH</td>
<td>20</td>
<td>yes</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>C2</td>
<td>ERH</td>
<td>40</td>
<td>no</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>C2W</td>
<td>ERH</td>
<td>40</td>
<td>yes</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>C3/A/B</td>
<td>ERH</td>
<td>20</td>
<td>no</td>
<td>A/B</td>
<td>no</td>
</tr>
<tr>
<td>C3/WA/B</td>
<td>ERH</td>
<td>20</td>
<td>yes</td>
<td>A/B</td>
<td>no</td>
</tr>
<tr>
<td>C4</td>
<td>VRH1</td>
<td>20</td>
<td>no</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>C4W</td>
<td>VRH1</td>
<td>20</td>
<td>yes</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>C5A/B</td>
<td>VRH1</td>
<td>20</td>
<td>no</td>
<td>A/B</td>
<td>no</td>
</tr>
<tr>
<td>C5WA/B</td>
<td>VRH1</td>
<td>20</td>
<td>yes</td>
<td>A/B</td>
<td>no</td>
</tr>
<tr>
<td>C6</td>
<td>VRH2</td>
<td>20</td>
<td>no</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>C6W</td>
<td>VRH2</td>
<td>20</td>
<td>yes</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>C7/A/B</td>
<td>VRH2</td>
<td>20</td>
<td>no</td>
<td>A/B</td>
<td>no</td>
</tr>
<tr>
<td>C7/WA/B</td>
<td>VRH2</td>
<td>20</td>
<td>yes</td>
<td>A/B</td>
<td>no</td>
</tr>
<tr>
<td>C8</td>
<td>VRH2</td>
<td>20</td>
<td>no</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td>C8W</td>
<td>VRH2</td>
<td>20</td>
<td>yes</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td>C9</td>
<td>VRH3</td>
<td>20</td>
<td>no</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>C9W</td>
<td>VRH3</td>
<td>20</td>
<td>yes</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>C10/A/B</td>
<td>VRH3</td>
<td>20</td>
<td>no</td>
<td>A/B</td>
<td>no</td>
</tr>
<tr>
<td>C10WA/B</td>
<td>VRH3</td>
<td>20</td>
<td>yes</td>
<td>A/B</td>
<td>no</td>
</tr>
</tbody>
</table>
[6], the effect of downwind refraction has also been found to be similar in 2D and 3D [35], and, moreover, calculations for urban mitigation schemes in 2D were found to be similar to 3D results [11].

The base scenario consists of ten urban street canyons, each with a width and height of 20 m. The canyon facades consist of brickwork and recessed window surfaces, see Fig. 1, with frequency independent normalised surface impedance values of $Z_n = 10$ and $Z_n = 77$ respectively (implying sound absorption coefficients of 0.33 and 0.05 for normal incident sound waves), as in Ref. [12]. As such, acoustic dissipation and diffusion is to some extent present in the street canyons. The roofs and ground have rigid surfaces and are flat. A sound source is located in the middle of the first street, with a source height of $z = 0$ m, representing road traffic. The sound pressure is computed for receiver positions as a function of the distance from the source at a height of 1.5 m above the street canyon ground surface, or positioned at the roof ($= 20$ m), see Fig. 3.

On top of the base scenario, the following variations are considered:

- Street widths of 40 m, with a total of eight street canyons;
- Building blocks with varying roof heights. The buildings either have a height of 20 m or of 26.4 m. Three scenarios are considered, with a variation in the height of the buildings;
- Roof parapets added to the edges of all buildings. The parapets either measure A) $0.2 \times 0.2$ m ($w \times h$) or B) $0.2 \times 0.4$ m ($w \times h$). The surfaces of the parapets are rigid;
- Vegetated roofs, with normalised impedance values and absorption coefficients for normal incident sound waves as shown in Table 2;
- Apart from the base scenario (C0), all scenarios are computed in the presence and absence of a wind field.

An overview of the scenarios can be found in Table 1.

### 3.2. Computational settings

#### 3.2.1. Computational fluid dynamics (CFD)

The domain sizes for the different configurations are based on the available best practice guidelines available (e.g. Ref. [36]). Fig. 2 shows the used 3D domain. Although sound propagation is computed in 2D, flow field simulations are performed in 3D to include any 3D flow effects present. For the width in the $y$-direction, a value of $2H_{\text{max}}$ is adopted, with $H_{\text{max}}$ the height of the street canyons (20 m). It is verified that widening the domain does not affect the velocities in the vertical centreline of the canyon. A fully structured grid is constructed using the grid-generation technique as presented in van Hooff and Blocken [37], consisting of cubical cells with size of 1 m in the street canyons and in the area up to 20 m above the street canyons. Above this height, the
Cells are stretched in vertical direction towards the top of the domain with a stretching factor of 1.26. The grid size is determined based on a grid-sensitivity analysis with four different grid sizes: 260,240 cells (10 cells over canyon width), 1,060,352 cells (16 cells over canyon width), 2,065,280 cells (20 cells over canyon width), and 3,526,272 (24 cells over canyon width) (Fig. 4). The results are discussed in Section 4.

A logarithmic mean wind velocity profile is imposed at the inlet:

Table 2
Absorption coefficient for normal incident sound waves and corresponding normalised surface impedance values adopted for the calculation of vegetated roofs.

<table>
<thead>
<tr>
<th>f (Hz)</th>
<th>63</th>
<th>125</th>
<th>250</th>
<th>500</th>
<th>1000</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha_n$ (−)</td>
<td>0.18</td>
<td>0.26</td>
<td>0.38</td>
<td>0.52</td>
<td>0.67</td>
</tr>
<tr>
<td>$Z_n$ (−)</td>
<td>20</td>
<td>13</td>
<td>8</td>
<td>5</td>
<td>4</td>
</tr>
</tbody>
</table>

Fig. 3. Sections of Configurations C1, C4, C6 and C9. Red dots represent the sound source positions, green dots represent the receiver positions. Dimensions in meter. Dashed rectangle is detailed in Fig. 1. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Fig. 4. Grids for grid-sensitivity analysis (canyon level) in vertical centreplane with 10 cells (a), 16 cells (b), 20 cells (c) and 24 cells (d) per canyon height and width.
with $u_{mag} = 0.41$ m/s the atmospheric boundary layer friction velocity related to the inlet mean wind speed profile, $k = 0.42$ the von Kármán constant, $z$ the height coordinate and $z_0 = 0.057$ m the aerodynamic roughness length [38]. The profile yields a wind velocity of 5.1 m/s at a height of $z = z - z_{roof} = 10$ m, which can be considered as a moderate wind speed. Turbulent kinetic energy $k$ is calculated from $k = u_{mag}^2 / \sqrt{C_w}$ with $C_w$ equal to 0.09, whereas the vertical profile of turbulence dissipation rate is determined from $\varepsilon = (u_{mag}^2) / \kappa (z_0 + z_r)$ [39]. Zero static gauge pressure is imposed at the outlet of the domain. No explicit surface roughness is imposed, i.e. window recessions are neglected, while limited implicit roughness is imposed using the sand-grain roughness height ($k_t = 0.19$ m) and the roughness constant ($C_t = 2.9$), which fulfil the requirements by Blocken et al. [40] for an aerodynamic roughness length of $z_0 = 0.057$ m. Note that the vertical velocity and turbulence profiles, the aerodynamics roughness length and the sand-grain roughness height are scaled down in the validation study, which is performed at wind-tunnel scale ($H = 0.106$ m instead of 20 m).

The steady RANS simulations are conducted with the realizable $k$-$\varepsilon$ turbulence model [20] to provide closure to the governing equations. Standard wall functions [41] with the sand-grain roughness modification by Cebeci and Bradshaw [42] are used to model the near-wall region. The SIMPLE algorithm is used for pressure-velocity coupling, pressure interpolation is second order and second-order discretization schemes are used for both the convection terms and the viscous terms of the governing equations. Convergence is assumed to be obtained when all the scaled residuals level off and reach a minimum value.

### 3.2.2. Computational acoustics

For the configurations of Fig. 3, a 2d equidistant spatial discretization with spacing $\Delta x = 0.1$ m has been used, corresponding to an upper 1/3 octave band of $f = 1700$ Hz. For all scenarios apart from the scenarios with a vegetated roof (C8 and C8W), a single calculation is carried out to compute the pressure response at all receiver positions. For the scenarios with a vegetated roof, a calculation is carried out per full octave band as one value of the roof impedance is used per band. The height of the computational domain is 70 m, and the boundaries are terminated by a perfectly matched layer (PML) spanning 50 cells, implemented as in Ref. [31]. The mean wind field components are included in the computational acoustic simulation. As the CFD grid does not correspond to the PSTD grid, the flow values have been mapped from the CFD grid to the PSTD grid, using linear interpolation.

### 4. Results

#### 4.1. Verification and validation

#### 4.1.1. Computational fluid dynamics

To validate the CFD simulations performed for this study, results from the steady RANS CFD calculations are compared with experimental data from a wind tunnel study by Kovar-Panskus et al. [43], who carried out measurements in a single street canyon. To determine the appropriate grid resolution for the RANS simulations a grid-sensitivity analysis is conducted using four grids (see Section 3.2.1). The results of the grid-sensitivity analysis for the dimensionless mean streamwise velocity ($U/U_{ref}$), as presented in Fig. 5, indicate that the grid with 2,065,280 cells (20 cells over canyon width) provides nearly grid-independent results and it is therefore used in the remainder of this study.

Fig. 6 shows $U/U_{ref}$ along five vertical lines in and above a canyon of a single urban configuration with a canyon width-to-height aspect ratio of 1.0, obtained from both the RANS simulation and the wind-tunnel experiment of Kovar-Panskus et al. [37]. The RANS data show a good overall agreement with the wind-tunnel data, especially for the left side of the canyon (Lines A and B). The velocity gradients in the canyon ($z/ H < 0$) as predicted by RANS are slightly smaller than in the experiments along Line C, D and E. The velocities above ($z_r/H > 0$) and just below roof height ($-0.1 < z_r/H < 0$) are very well predicted along all five vertical lines. Overall, it is concluded that the predicted flow pattern inside and above the canyon provides a good agreement with the data from the wind-tunnel experiment. The grid resolution and model settings and parameters as used in the verification and validation study are therefore used for computing the wind field for the configurations of Table 1.

#### 4.1.2. Computational acoustics

Calculations with the PSTD method have been found to be in good agreement with results from literature [8] for a scenario of sound propagation over the urban roof level [44].

For the complex scenarios with wind in this paper, results for different grid spacings will show the grid convergence of the method with respect to its accuracy. Fig. 7a shows $\Delta W_{EC}$ results for two calculations for scenario ERH, for grid spacings of $\Delta x = 0.05$ m and $\Delta x = 0.1$ m. These spacings would allow for a maximum frequency of 3400 Hz and 1700 Hz, respectively. The $\Delta W_{EC}$ results show to be very similar, apart from the 1600 Hz 1/3 octave band result. The results are also listed in Table 3. All further calculations are performed with the $\Delta x = 0.1$ m grid spacing and following the convergence results from Table 3, it needs to be emphasised that the 1600 Hz 1/3 octave band result could have an error in the order of 1 dB.

Another verification of the PSTD results is for the different ways of including the mean flow in the acoustic equations, either by solving the equations (2) or by using the simplified effective sound speed approach of equation (3) in Fig. 7b. The results for configuration 4 solved by the LEE-equations and $\epsilon_{eff}$-equations (Eq. (3)) are very similar, showing that the horizontal wind components are dominant in determining the wind effect on urban sound propagation in this scenario. Since the results from the LEE and $\epsilon_{eff}$ are similar, the simplified $\epsilon_{eff}$-equations approach is taken for all configurations.

#### 4.2. Results without wind

The impulse response at receiver position (440 m, 1.5 m), i.e. in the middle of the last street canyon of the configurations, is shown in Fig. 8. The response shows contributions from a multitude of sound waves, which are reflections from the facades in the street of the source as well as in the street of the receiver. The shape of the impulse response is similar to data of previous studies in street canyons where the receiver is shielded from the sound source by a building block [8] [45]: the amplitude of the response increases after the first sound arrival and after some point in time the response decreases. The time it takes the impulse response to reach the maximum value, the rise time, is increasing with frequency. The $\Delta L_C$ for configurations C1 and C2 is plotted in Fig. 9a, i.e. the sound pressure level relative to the configuration without buildings. A more or less linear increase of shielding can be found, which is known from theories on shielding of sound by (thick) barriers. Also, the effect of intermediate street canyons was found not to be frequency dependent [8], explaining that the diffraction related frequency dependency is kept in the results. The results for configurations C1 and C2 are quite similar. It is important to note that the values of $\Delta L_C$ for high frequencies imply that the sound pressure levels in reality will end up below the background noise level from other (closer) sound sources. Low-frequency sounds could still be audible, especially if the sound source produces high sound levels.

In addition to the base configuration C1, three different roof height scenarios are included, which are shown in Fig. 3. The scenarios imply more shielding (VRH1 and VRH3) by taller building blocks between source and receiver, or less shielding by taller building blocks at the extremities of the domain (VRH2). The $\Delta L_C$ results from these configurations, numbers C4, C6 and C9, are shown in Fig. 9b-d. Fig. 9b-d indeed illustrates that VRH1 (C4) and VRH3 (C9) lead to lower values...
compared to configuration C1, while VRH2 (C6) has higher values for low frequencies and somewhat lower values for high frequencies. The results indicate that the shielding effect for urban scenarios is highly dependent on the topology: while the urban variations here are still rather modest (increased roof level by 6.4 m or about 30% of the original building height). A difference of up to 20 dB is found.

Results for added roof parapets - C5, C7 and C10 - are shown in the same figures as for the VRH scenarios, indicated with white markers. The lower lines are for the tallest parapets. Although the parapets are quite small (up to 0.4 m tall), they may lead to a further reduction up to 7 dB at high frequencies. For low frequencies, the configurations with parapets could even enlarge the levels.

For VRH2, configuration C8 with vegetated roofs is computed. The results show the expected decrease of sound levels, mostly for the highest frequencies. The absorption coefficient for the highest frequency is largest, see Table 2, partly explaining these results. When computing the effect of a roof with the impedance for 1000 Hz (and thus absorption) for the whole frequency range the frequency dependency is much less clear. This is shown by the dashed line in Fig. 9c.

### 4.3. Results with wind

For a better interpretation of the wind effect, WE results are first shown as a function of both the frequency and the receiver position for C1W in Fig. 10. The receiver positions in all streets are shown over distance. For the locations in between the streets, receiver positions at roof level (z = 20 m) are taken. Vertical lines are plotted to indicate the location of the street canyon edges. The trend of the results is that \( W_{C1} \) increases with distance, with a faster increase for the higher frequencies. For frequencies above 125 Hz \( W_{C1} \) reaches a first maximum, which is located at further distances for lower frequencies. Beyond these local maxima, the results fluctuate over distance. This fluctuation is due to the interference of the multiple sound waves in the downward refracting atmosphere.

For the ERH cases of 20 m and 40 m wide street canyons, Fig. 9e displays the wind effect for the scenarios with wind, i.e. \( W_{C1} \) and \( W_{C2} \). Clearly, the wind effect is very large, over 25 dB. Fig. 9e also shows \( L_{C10} \), which indicates that the wind has reduced the shielding of the urban topology to the range of 10–20 dB.

The results for VRH1 are shown in Fig. 9f. The level relative to ERH, \( L_{C1W} \), clearly shows that in the presence of wind, the levels in the last street canyon are similar for the ERH and VRH configurations: shielding by the intermediate canyons is now rather identical. The effect of the roof parapets is not very significant for the broad frequency range. The wind effect for VRH1 as measured by \( W_{C4} \), shows that the effect is even larger than for the ERH configurations.

Fig. 9g contains the results for the VRH2 scenarios. Clearly, the effect of elevated buildings at the outside of the configurations has a deteriorating effect on the noise levels in case of the downward refracting scenario: the \( L_{C1W} \) values are positive for all frequencies. Also the wind effect measured by \( W_{C6} \) is larger than for the ERH configuration. Roof parapets have a rather insignificant effect on reducing the wind effect.

An interesting result is obtained for the vegetated roof configuration...
Fig. 6. (a–e) Comparison of \( U/U_{\text{ref}} \) from experiments (symbols [43]) and CFD (solid line) along five vertical lines (Line A-E). a) \( x/W = 0.151 \); b) \( x/W = 0.302 \); c) \( x/W = 0.5 \); d) \( x/W = 0.698 \); e) \( x/W = 0.849 \). f) Indication of location of five vertical lines used in the comparison.
C8W. Whereas the vegetated roofs increase the shielding effect without the presence of wind, their effect is almost insignificant in the presence of wind. This can be explained by the fact that sound waves that reach the receiving street are bent over the rooftops and have a lower amount of interaction with the rooftops as for the configuration without wind. A calculation with the same roof impedance for all frequencies (dashed lines) shows that a damping is still present at low frequencies.

Finally, the configurations with VRH3 are shown in Fig. 9h. Also for these configurations, the wind effect increases the sound levels for all frequencies, and it is comparable with the increase for the ERH configuration for low frequencies. However, the increase is more moderate compared to the VRH1 and VRH2 configuration. An important result here is that the roof parapets do have a significant influence on the results. Especially above 500 Hz, the $L_{CBB}$ values decrease rapidly with increasing frequency. Clearly, the wind does not have a strong effect for the high frequencies in the presence of the parapets as compared to ERH.

### 4.4. Broadband results

To place the results in perspective, the most important broadband results are computed and shown in Fig. 11. The broadband effect of roof parapets is not shown as they all remain within 2 dB(A). $L_{CBB,0}$ is the broadband level relative to the configuration without buildings and without wind (see Eq. (10)). For the configurations without wind, $L_{CBB,0}$ is very low, from $-32.8$ dB(A) for VRH2 (C6) down to $-49.4$ dB(A) for VRH3 (C9). Assuming the road to be populated with a total number of 20,000 vehicles per hour at a speed of 30 km/h, the sound level at 440 m distance for configuration C0 is 58.0 dB(A). Therefore, with these insertion losses the sound levels are reduced below typical urban background noise levels of 45 dB(A) [46].

### Table 3

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<th>f (Hz)</th>
<th>A</th>
<th>B</th>
<th>C</th>
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<td></td>
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**Fig. 7.** a) CA grid convergence: $W_{ECW}$, computed with a discretization of $\Delta x = 0.05$ m and $c_{eff}$-approach (solid line, open circles), a discretization of $\Delta x = 0.1$ m and $c_{eff}$-approach (solid line, solid circles), b) CA equations: a discretization of $\Delta x = 0.1$ m and $c_{eff}$-approach (solid line, solid circles), discretization of $\Delta x = 0.1$ m and LEE approach (dashed line, solid circles).

**Fig. 8.** Computed normalised impulse responses at receiver position (440 m, 1.5 m), i.e. in the last street canyon, for a) C1 and b) C1W.
Fig. 9. Relative levels and wind effects computed for a) C1 (solid line, closed circles) and C2 (solid line, open circles), b) C4 (solid line, closed circles), C5A (solid line, open circles) and C5B (dashed line, open circles), c) C6 (solid line, closed circles), C7A (solid line, open circles), C7B (dashed line, open circles), C8A (solid line, green solid circles) and C8B (dashed line, green solid circles), d) C9 (solid line, closed circles), C10A (solid line, open circles) and C10B (dashed line, open circles). Legends for subplots e)-f) as subplots a)-d), but for configurations with wind. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)
The broadband wind effect is about 15 dB(A) for the ERH and VRH3 configurations, and around 22–23 dB(A) for the VRH1 and VRH2 configurations. This increases the $L_{C_{0,0}}$ to values between −20 and −10 dB(A) for the ERH, VRH1 and VRH2 scenarios. Only the VRH3 scenario has a value lower than −30 dB(A). In particular for VRH2, the level is only around 10 dB(A) lower than the configuration without buildings, indicating that distant sound sources may be audible for urban scenarios where the source is highly shielded from the receiver.

The effect of the vegetated roof (C8 and C8W) is clear in Fig. 11. The reduction is about 4–5 dB(A) compared to the configuration without vegetated roofs (and even around 10 dB(A) if the low-frequency absorption of the roof would be higher) for the case without wind, but only 1–2 dB(A) for the configurations with wind, even when low-frequency absorption at the roofs is present.

5. Discussion

The effect of a downward refracting atmosphere on sound propagation over a flat ground surface was reported in literature to lead to a significant sound pressure level increase (in the range of 10–20 dB) compared to the scenario without wind [31] [47]. Thus far, the effect of a downward refracting atmosphere for an urban topology with multiple street canyons on a larger distance has not been reported. The results of Section 4 show that the wind effect is even larger than reported for a flat ground scenario, in particular for the highest frequencies. This result was found before for the case of two parallel street canyons [7], and can be explained by the diffraction shielding compensation: the shielding by the urban topology without wind is higher for the higher frequencies, see Fig. 9a, and in the presence of a wind field, the shielding is reduced due to the curvature of the sound waves, which therefore mostly influence the highest frequencies. This effect is described in more detail elsewhere [11].

The spectral values of the computed wind effects (red lines of Fig. 9e–h) are not expected to be occurring in reality, as urban background noise levels will act as a lower bound of the sound level. Also, the scenarios considered contain both a street canyon at the source side as at the receiver side, and might be different when no multiple sound reflections occur, either in the source or receiver environment.

From the results of Section 4, summarised in Fig. 11, it can be concluded that the wind effect seems to be highly dependent on the urban configuration. In this paper, only a limited number of variations have been considered with respect to roof heights, roof parapets, and roof impedance. From the variation in the wind effect of configurations VRH2 and VRH3, it is observed that the actual wind effect can be drastically different dependent on the local geometry around the sound source and receiver. There is thus a significant uncertainty concerning the local wind effect in urban areas, the effect of wind depends on various aspects: location of receiver and source, urban topology with its material properties and wind field. A downward refracting atmosphere may to a large extent cancel the diffraction shielding caused by the urban topology, but this can be influenced by the local surroundings close to the receiver and source.

One of the very interesting aspects of the predictions is the role of vegetated roofs. Although only computed for configuration VRH2, it is remarkable that the sound reduction by vegetated roofs is limited in the presence of a downward refracting atmosphere. This result could be explained by the fact that sound waves in a downward refracting atmosphere have a lower degree of interaction with the underlying urban roofs. At the same time, this interaction with the urban roofs is largest for the lowest frequencies (because of the larger wavelengths of these frequencies) and therefore the potential of reducing sound in a downward refracting atmosphere by changing the roof impedance is highest for these frequencies, see Fig. 9g.

Note that the change of surface roughness due to a vegetated roof is not included in the CFD simulations of the wind field; however, the effect of surface roughness on the mean velocities is generally expected to be very limited (e.g. Blocken et al. [48]), since flow separation occurs at the sharp edges of the buildings and not at the roof surface itself. Moreover, a modified surface roughness only affects the flow in a small part of the very thin boundary layer above the roof and the effect of an altered surface roughness on the velocity field further away from the
roof, and especially in the canyons, will be very limited.

The results of this computational study are restricted for the chosen configurations and adopted settings. Some important factors in this respect are:

- Uninterrupted street canyons. The calculations are done in 2D, which assumes that the geometry is invariant in the third dimension. This implies uninterrupted street canyons. Interruptions of street canyons, especially if these are close to the location of source or receiver, would change the results as the number of facade reflections reaching the receiver might then be limited. Therefore, the predicted wind effects should be considered as an upper limit for urban configurations that are close to the studied configurations.

- Dimensionality. It has already been found in previous work that calculations in 2D are very close to results in 3D for the same urban configurations [6] [11] [35]. However, due to its implicit assumption of the invariance in the third dimension, the configurations lead to upper limit results as pointed out by the previous bullet point.

- Only one wind scenario. The wind fields computed in this work only assume one wind velocity at reference height for all cases. The effect of the wind on the sound pressure levels depends on the reference velocity used, but the possible linearity of these variations is the subject of future work. At the same time, the adopted scenario does not include temperature gradients, which could have an important role as well. Besides, any effect of turbulent scattering is not computed either. However, these effects are relevant for an upward refracting atmosphere [3], and not for the downward refracting scenarios of this work.

- Atmospheric absorption. No atmospheric absorption has been adopted in the modelling with PSTD. The effect at the highest frequency considered is about 2 dB in the furthest street canyon [3]. As the effects presented are always shown relative to a scenario at the same distance, the effect of atmospheric absorption is rather low. However, it is included in the calculation of the broadband effect by including it in the reference sound pressure levels from road traffic.

- Wind flow modelling approach. RANS has been used to model the wind flow. Future research will also focus on large eddy simulation (LES), in which the large scales of turbulent motion (eddies large than filter size) are resolved. LES is much more costly than RANS, but might be needed for flow fields where accurate predictions of turbulence levels are of importance. In addition, unsteady flow effects can be accurately predicted by LES, which might improve the prediction accuracy of sound propagation in cases with highly transient wind flows.

6. Conclusions

This work presents, for the first time, a prediction of the effect of a downward refracting atmosphere on distant sound propagation over generic urban configurations with multiple street canyons. The study uses a two-step approach, by first computing the wind field from computational fluid dynamics (CFD), and then adopting the mean wind field in a computational acoustics (CA) method.

An urban configuration is studied with a sound source in a street canyon, representing road traffic, and receivers located in a distant street canyon (at 440 m), which are separated by multiple urban building blocks.

For the CFD method, calculations with steady RANS are carried out and it is found that the RANS approach can accurately predict the flow field within and above a single street canyon based on a comparison with experimental data from literature. For the computational acoustics approach, for which PSTD is used, a comparison of solving the linearized Euler equations at one hand and the linear acoustics equations with the effective sound speed approach at the other hand reveals that for the studied urban scenarios, the effective sound speed approach gives a good approximation. Results from calculations for the various configurations reveal that:

- The increase of sound levels due to the presence of a downward refracting atmosphere is larger for higher frequencies;
- The wind effect may reach over 30 dB for single 1/3 octave band and ranges from 15 to 23 dB(A) assuming road traffic noise as sound source;
- The urban topology close to the source and receiver can largely influence sound levels in the presence of wind. Tall buildings behind source and receiver are not favourable, while tall buildings in front of source and receiver are favourable;
- Roof parapets can shield noise levels at shielded locations in urban areas at high frequencies, but the broadband effect for road traffic is limited;
- Vegetated roofs have the potential to reduce sound levels without wind, but in a downward refracting atmosphere the broadband effect is small (< 2 dB(A)). An exception are the low frequencies, where reductions up to 10 dB(A) in the presence of wind were found, but only if vegetated roofs are applied with significant low-frequency sound absorption. This indicates that for some noise sources with a high low-frequency content as urban music concerts and airplanes, roofs with low-frequency absorption have a potential.

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