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2aPAb2. A numerical approach to the climatology of near-surface sound levels
Sylvain Cheinet*

*Corresponding author's address: French-German Research Institute of Saint-Louis (ISL), 5 Rue General Cassagnou, Saint-Louis, 68440, -, France, sylvain.cheinet@isl.eu

The near-surface sound levels propagated at distance from a known source show a large variability on the long term. This variability is essentially caused by the weather-dependence of the refractive characteristics: wind and temperature stratifications, turbulence. An approach to document this variability is to simulate the sound propagation under these varying characteristics at the selected site. This study uses a numerical model which physically describes the sound propagation including in presence of turbulence. The model is based on the parabolic equation, it ingests standard atmospheric parameters as input. The predicted sound levels for an example 40Hz-frequency sound propagating at a 1.5km-range are shown to combine the impacts of stratification and turbulence. The results are used to form the sound level climatology at several sites over the globe, based on existing climatological data. The obtained statistics are modulated by the dominant wind regimes, the seasonal and diurnal cycles. The sensitivity of these results to turbulence assessment is discussed.

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I. INTRODUCTION

The near-surface sound levels received at distance from an emissive source critically depend on the propagation conditions. Besides the geometrical spreading, the ground partly absorbs the signal. The atmospheric stratification in wind and temperature creates upwind shadow zones and downwind ducts. The refractive turbulence drives the sound levels in the shadow zones. Because the ground characteristics, the atmospheric stratification and turbulence properties change with site and time, the propagated sound levels feature some considerable variations.

These variations pose constraints on the configuration and performance of sensing systems (size of antenna, operating range), on the design and use of noisy infrastructures (airports, roads, military proving grounds, industrial plants etc) and on the assessment and management of environmental noise (e.g. the 2002/49/EC directive). Thus, it is of wide interest to document and predict these variations. First, sound level statistics on the long term can reveal the significance of the induced constraints, which can be integrated in the definition step, before development and operation. Second, corrections to the short-term predictions of propagation effects may be accounted for in the signal sensing (Ostashev et al., 2012) or in the mitigation of noise pollution (e.g. Sharman et al., 2000).

The variability of sound levels may be directly documented through in-situ acoustic measurements (Gauvreau et al., 2010). This approach is restricted to sites with heavy equipment and monitoring. Alternatively, one may couple meteorological data to a sound propagation model. The data may come from measurements (Heimann and Salomons, 2004, Ecotière, 2008). Recourse to data from numerical weather prediction systems allows a more general assessment (van der Eerden and van den Berg, 2008, Wunderli and Rotach, 2011).

One major limitation of the approach based on sound propagation modeling is the challenging description of turbulence scattering. Cheinet (2012, hereafter C12) develops a method to alleviate this limitation. The method analytically parameterizes the stratification and turbulence profiles in the near-surface atmosphere in terms of standard numerical weather predictions. It then simulates the sound propagation in presence of ground effects, stratification and turbulence. This model has the potential to provide some physically-based sound level predictions and statistics under general environmental conditions, i.e. for arbitrary sites and periods.

The present study describes the overall method, and investigates its predictions for the sound level statistics over two sites. The paper is composed as follows. Section II discusses the environmental characterization of the selected sites. Section III presents the sound level modeling approach adopted in this study, which follows and generalizes the approach of C12. Section IV investigates the sound level statistics obtained over the sites. Section V summarizes the results.

II. ENVIRONMENTAL PARAMETERS

The four environmental parameters which are considered to dominantly drive the outdoor sound propagation are:

- The friction velocity $u_*$ (in $\text{m} \cdot \text{s}^{-1}$). This parameter is a major driver of the mean wind stratification. A stronger $u_*$ stands for larger winds, i.e. enhanced wind effects on the sound levels,

- The surface buoyancy flux $F_b$ (in $\text{K} \cdot \text{m} \cdot \text{s}^{-1}$). Qualitatively, the adiabatic temperature lapse rate varies with $F_b$ and is opposed to it. When the radiative forcing drives the surface fluxes over land, the buoyancy flux is negative at night, slightly positive on overcast days and positive on fair-weather days,

- The near-surface wind direction $\theta_{\text{wind}}$. The angles are taken with the convention 0° Eastward, 90° Northward etc. Wind turning with height is not accounted for.

- The ground impedance. Hereafter $Z_b$ denotes the complex impedance normalized by a reference density and sound speed. A larger module of $Z_b$ stands for a more reflective surface.

We now discuss our prescription of these input environmental parameters. An atmospheric database is used to document $(u_*, F_b, \theta_{\text{wind}})$ for various sites and times. The database production procedure follows Cheinet et al. (2011). It is based on the Integrated Forecast System (IFS) model developed at the European Center for Medium Range Weather Forecasts (ECMWF). For every considered day at 0000 UTC, a 24-hour global IFS forecast is performed with the ERA-Interim atmospheric re-analysis as initial state. The IFS version is CY31R2 with 60 vertical levels and a horizontal discretization with 255 spherical-harmonic wave-numbers. The chained 24-hour forecasts form a hourly database over consecutive days.
The database includes five months of July and five months of January from 1999 to 2003. This time frame captures the climatological specificities of each site, while preserving the signatures of the diurnal and seasonal cycles. The diagnostics are extracted on a 1°×1° grid in latitude and longitude, which approximately amounts to a 100km×100km horizontal resolution. They include $u_*$, $F_b$, and $\theta_{\text{wind}}$ as calculated at the first model level (10m above the ground). The surface layer treatment of the IFS decomposes each grid-box of the model on a basis of eight tiles. Each tile stands for a surface type, with e.g. specific surface fluxes. Here we focus on the tile corresponding to low vegetation. Accordingly, the normalized ground impedance is set to $Z_b = 31.4 + i38.5$.

The first selected site (S1) is located at 7°E, 53°N. Figure 1 illustrates that in summer, this site is affected by changing meteorological conditions. There is a prevalence of West winds. The moderate surface buoyancy fluxes presumably point back to frequent disturbed weather. The January data (not shown) show a more pronounced prevalence of South West winds, with enhanced $u_*$ (stronger winds). The surface buoyancy fluxes are bounded in the interval $[-0.1, 0.05] \text{K} \cdot \text{m} \cdot \text{s}^{-1}$, consistent with the modest radiative forcing in mid-latitude winter. These results are all consistent with the oceanic climate of North-Western Germany. The second site (S2, at 5°E, 44°N) is in the Rhone valley (South-Eastern France). Compared to S1, it features larger daytime buoyancy fluxes in both winter (not shown) and summer, and a major prevalence of North-North-West winds (fig. 1). Again, these results are consistent with the Mediterranean climate expected at S2 (frequent fair weather), combined with the impact of Mistral regional wind.

**Figure 1**: Statistical distributions of (left) $\left( F_b, u_* \right)$ and (right) $\theta_{\text{wind}}$, as obtained in the IFS database. The data are for the five July months, all hours together (5×31×24 data points in each panel), at sites (top) S1 and (bottom) S2. The figure uses the discretization intervals of the environmental sampling of Table 1.

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III. SOUND LEVEL CALCULATIONS

Sound level modeling

This Section recalls and generalizes the approach of C12 to model the near-surface sound levels propagated from an acoustic source from the input environmental conditions \((u_s, F_b, Z_b, \theta_{\text{wind}})\). More exactly, we characterize the propagation effects through the mean relative sound level, defined as the sound level (in dB) averaged over turbulent fluctuations and relative to propagation with only the geometrical spreading.

The first step in this calculation is to derive the vertical profiles of the effective parameters for atmospheric refractive effects, for stratification (term \(\mathcal{E}_{\text{mov}}\) in C12) and turbulence (term \(b_c\) in C12). The formulation depends on \(u_*\), \(F_b\) and \(\theta\), where \(\theta = \theta_{sr} - \theta_{\text{wind}}\) is the propagation direction relative to the wind and \(\theta_{sr}\) is the source-to-receiver angle. The calculation is based on Monin-Obukhov Similarity (MOS). As argued by C12, MOS allows a consistent description of stratification and turbulence in the atmospheric surface layer over flat, homogeneous surfaces, and under not too stable conditions. The limitation to low atmospheric levels implies that the propagation range is typically limited to 2km. Another assumption is that the turbulence is given by temperature and wind fluctuations with uncorrelated von Karman auto-correlation spectra.

In the second step, a sound propagation model uses the prescriptions for source, receiver, ground and atmosphere, and makes a prediction of the average sound level on a (range, height) grid. The formulation is based on the Parabolic Equation (PE) formalism (C12). The PE formalism is particularly well-suited for near-surface propagation scenarios. Our PE model incorporates a finite-impedance ground parameterization. Among others, this accounts for absorption of the acoustic wave by the ground. The accounting for turbulence scattering in the PE increases the computational cost of the method, but allows capturing the physics of mean sound levels in shadow zones. Still, it does not describe the instantaneous variations of sound levels due to turbulence intermittency.

Very stable thermal stratification typically occurs on clear nights with low winds over land (low \(u_*\), negative \(F_b\)). On the propagation point-of-view, they induce downward refraction, so the atmospheric levels of relevance to propagation remain close to the surface. We hereafter assume that the heights \(z < 40m\) are relevant in these conditions. There is a general lack of understanding of the atmospheric stratification and turbulence characteristics in these very stable conditions. MOS is valid for heights such that \(z/L < 2\), where \(L\) is the Obukhov length \((L \propto -u_*^3/F_b\), see C12). For \(L < 20m\), the ratio \(z/L\) is greater than 2 at some heights of relevance for propagation, but the atmospheric characteristics can not be diagnosed reliably, so the above approach is not appropriate. A direct parameterization of the sound levels is used instead, which extends the model of C12.

Let \(S(u_*, F_b, Z_b, \theta)\) denote the relative sound level for given propagation conditions. Let \(\bar{u}_s\) denote the value of \(u_*\) such that \(L = 20m\) for the considered buoyancy flux. The selected parameterization is an interpolation with the upper boundary, supposed to be the value calculated downwind for \(u_* = \bar{u}_s\):

\[
S(u_*, F_b, Z_b, \theta) = S(\bar{u}_s, F_b, Z_b, \theta) + \frac{u_*}{\bar{u}_s} (S(\bar{u}_s, F_b, Z_b, \theta) - S(\bar{u}_s, F_b, Z_b, 0)) 
\]

This parameterization provides continuity in the predictions, and produces two physical expectations: the sound levels increase with decreasing \(u_*\), and are independent on the wind direction at very low \(u_*\). Still, the essentially ad-hoc character of this formulation promotes a cautionary analysis of the predictions under these conditions.

Sound level database

From the above prescriptions and processing, a realization of the parameters \((u_*, F_b, Z_b, \theta_{\text{wind}})\) can be attached to a mean relative sound level at a receiver in the direction \(\theta_{sr}\). In order to avoid repeating the calculations for similar propagation configurations, a common practice e.g. in noise management studies is to perform the sound propagation calculations in advance, over a set of representative classes of the environmental conditions. Here we follow this approach within the following applicative scenario. The source is at a height of 2m, and emits at the
frequency 40Hz. At this low frequency, the absorption of sound by air is negligible. The receiver is taken at height 1m and at range 1500m from the source. MOS analytical relationships are discretized with a one-meter resolution on the vertical. The spatial resolution of the sound propagation model is also set to 1m, the computational domain is 500m high and 2000m long.

The free parameters of the propagation calculation are \((u_*, F_b, Z_b, \theta)\), and the wind effects are symmetric with \(-\theta\). The present study systematically samples these parameters to pre-calculate the sound levels. The basis for this sampling is given in Table 1. C12 examines the sound levels with varying \((u_*, F_b)\), for \(\theta = 180^\circ\) (upwind direction) and one value of \(Z_b\). In comparison, the present database extends the analysis in \(\theta\) with a sampling every 23°, and with three values of the ground impedance. At the considered source frequency, these values stand for absorbing, well-reflective and extremely reflective surfaces. The database spans over a wide range of propagation conditions, and contains a majority of atmospheric configurations met over flat terrain over Earth.

### Table 1: Sampling of \((u_*, F_b, Z_b, \theta)\) in the database.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>(u_* (m \cdot s^{-1}))</th>
<th>(F_b (K \cdot m \cdot s^{-1}))</th>
<th>(Z_b) (normalized)</th>
<th>(\theta) (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sampling</td>
<td>Linear, 49 values</td>
<td>Linear, 51 values</td>
<td>Linear, 9 values from -0.21 to 0.81</td>
<td>Linear, 9 values from 0 to 180</td>
</tr>
<tr>
<td></td>
<td>from 0.04 to 1</td>
<td>from 6+8i, 31.4+38.5i, 103+125i</td>
<td>6+8i, 31.4+38.5i, 103+125i</td>
<td>0 to 180</td>
</tr>
</tbody>
</table>

Figure 2 illustrates the sensitivity of the predicted mean relative sound levels to the atmospheric conditions. In the upwind case (\(\theta = 180^\circ\)), the sound levels decrease with the adverse wind and increase with the absolute value of the surface heat flux. As discussed by C12, this latter result relates to enhanced turbulent scattering. At very low wind forcing though, the stable thermal stratification may be sufficient to yield favourable conditions to propagation. As \(\theta\) decreases, the unfavourable wind effect reduces, vanishes crosswind, and eventually becomes favourable downwind. The sound level is then relatively constant (approx. 12dB). The fringes pattern in downwind conditions is caused by the interferences between the reflected and direct signals. It is still apparent despite the de-correlating impact of turbulence. It will be seen below that the sound levels in downward refractive cases (downwind and under stable thermal stratification with low winds) show a notable sensitivity to the ground impedance.

**FIGURE 2**: Simulated relative sound level (dB) with the surface buoyancy flux and the friction velocity. Each panel stands for a propagation direction relative to the wind. The normalized ground impedance is \(Z_b = 31.4 + i38.5\).

The above results show that a sound propagation model must account for mean stratification, turbulence scattering and ground absorption in order to reliably quantify the sound levels in arbitrary environmental conditions for the selected scenario. Note that the ground impedance should depend not only on the surface type, but also on the meteorology e.g. through the ground water content. This indirect sensitivity to atmospheric conditions is not accounted for in the present approach. The sensitivity to other surface characteristics entering MOS calculations (e.g. roughness length, see Appendix of C12) is of second order compared to the present variations.
IV. SOUND LEVEL STATISTICS

Sec. II provides the parameters \( (u_* F_b, Z_b, \theta_{\text{wind}}) \) for the selected sites and times. For each time and site, and for a given \( \theta_{\text{sp}} \), the mean relative sound level in the direction \( \theta \) is derived as the level calculated at the nearest coordinates in the pre-calculated database of Sec. III. We now illustrate the obtained sound level statistics for the considered sites.

As a preliminary remark, it can be noted that the discretization chosen for the environmental parameters (Table 1) appears to be adequate to sample the distributions of fig. 1. Also, it appears that the very stable conditions (negative \( F_b \), small \( u_* \), leading to the use of Eq. 1) are only marginally present in the atmospheric statistics at S1 and S2. This result may appear as a combination of (i) the low occurrence of these conditions at the selected sites, and (ii) the difficulty in capturing these conditions in the IFS model.

Figure 3 shows the statistical distribution of the mean relative sound levels for July at S1, for four propagation directions. First, the sound levels vary in the range between -20dB and 15dB. Such major variations cannot be ignored in the operation of noisy activities and in the design of sensing systems. The favorable conditions have the most probable value of 12dB. This result is in lines with the result obtained by C12 (e.g. his fig. 6), according to which the sound level takes a relatively uniform value in downward refractive conditions. The West wind prevalence enhances the probability of large sound levels Eastward. Conversely, the frequently adverse propagation conditions in the Westward direction cause a peak occurrence at -17dB.

Figure 3 also shows the same analysis at site S2. The contrast with the statistics at S1 is notable. At this site, the North-West winds favor propagation in the South and East directions, with a large occurrence of low sound levels in the North direction. For both sites, the consistent occurrence of large sound levels in the directions opposed to the dominant winds implies that wind effects are sometimes either favorable or not significant enough to balance the thermal stratification (e.g. at night time with low winds).

The above statistics gather all hours of the day for a single season. Since the meteorological conditions feature some diurnal and seasonal variations, it may be expected that the sound level statistics are modulated at the same time scales. Figure 4 illustrates the statistical distribution of the sound levels at S1 for Westward propagation, at 00UTC and 12UTC, and for July and January months. Each distribution is obtained from 5x31 data points. In the midday of July, the most probable value of the sound level corresponds to the unfavorable conditions (-17dB). This results from the combination of an unfavorable wind-induced refraction and an unfavorable thermal stratification. The midnight of July still features a peak at -17dB, but the most probable sound level is under favorable conditions. When still adverse, the wind forcing is rarely sufficient to counter-balance the favorable impact of (stable, downward refracting) thermal conditions. Conversely, in January, the night-time sound levels are low. The impact of the temperature stratification is apparently dominated by the wind-induced refraction, consistent with the more frequent and more intense South West winds.
The above analysis does not discriminate between the impacts of turbulent fluctuations and mean stratification. Physically, these atmospheric characteristics are correlated. Still, it is numerically possible to pin-point the impact of turbulence scattering. To do so, we have modified our sound propagation model as follows: the mean relative sound levels are calculated without turbulence i.e. with $b_z = 0$, while a minimum threshold is set as -21dB. As shown on fig. 5, this procedure results in a major peak at the selected threshold, which replaces the -17dB peak. According to this sensitivity test, turbulence tends to increase the sound level in shadow zones in a statistically significant manner, increasing the occurrences of levels in the range [-20,-8]dB. Another minor difference is the occurrence of larger sound level maximum (above 15dB) without turbulence, as a result of non-blurred interferences between the direct and ground-reflected signals.

Last, we have tested the impact of ground characteristics by changing the normalized ground impedance to $Z_g = 6 + 8i$. Leaving the meteorological conditions unchanged, the physical picture is that of a bank of sand surrounded by a large grass area. The obtained statistics (fig. 5) are shifted toward lower sound levels, due to the enhanced ground absorption. The favorable refractive conditions induce a number of reflections on the ground. The relative sound levels in these conditions are negative (peak at -12dB), at odds with the behavior over reflective grounds. This sensitivity of sound level statistics is consistent with the results of Heimann and Salomons (2004).

V. SUMMARY AND CONCLUSIONS

Sound levels feature a large variability caused by environmental factors, including the ground, atmospheric turbulence and atmospheric stratification characteristics. Predicting this variability on the short and long terms is important e.g. to improve the acoustic sensing capacities and to mitigate the noise pollution. This is a challenging task because the impacts of these coupled physical parameters on sound propagation are difficult to measure and to model. For a given propagation scenario, a standard approach is to introduce a set of representative classes for the environmental conditions, and use a numerical model for sound propagation to quantify the sound levels in each
class. From observed or predicted environmental conditions, one may then interpolate the sound level from the nearest point in the database.

In this study, the classes are discriminated from the ground impedance, the near-surface wind and buoyancy forcings and the wind direction. The atmospheric turbulence and stratification characteristics are consistently derived from these parameters. The sound propagation model is based on a second-order moment parabolic equation which accounts for mean refraction, turbulence scattering and ground absorption. The model has two limitations, which point back to challenges in the field of atmospheric physics. First, the use of surface layer similarity limits the sound level predictions to ranges lower than some kilometres. Second, an ad-hoc parameterization of the sound level is introduced in very stable conditions.

The model is used to form a database of the near-surface sound levels at the range 1500m and height 1m from a low frequency near-surface source. Atmospheric conditions unfavourable to propagation are in the upwind directions with non negligible wind forcing over reflective ground, and also downwind over well-absorbing ground. Over reflective grounds, favourable conditions are met downwind and also under stable thermal stratification. The long-term statistics of sound levels are examined for two sites in North-Western Europe. The ground impedance is set as a fixed parameter. The atmospheric quantities are obtained from a long-term weather database, with an additional processing to access the products at an hourly rate. The analysis demonstrates several results:

1. Our approach allows short-term predictions (deterministic forecast) and long-term assessment (climatological statistics) of the sound levels based on operational weather data.
2. For the selected sites and periods, the mean relative sound levels vary over the range [-20,15]dB, with maximal occurrences corresponding to unfavourable (-17dB) and favourable (12dB) conditions.
3. Besides mean atmospheric stratification and ground absorption, the quantitative statistics at the selected sites and times notably depend on turbulent scattering due to the significant occurrence of upward refractive shadowing.
4. The statistics are modulated by site-dependent climatological features: dominant wind regime, occurrence of fair weather, diurnal and seasonal cycles in the environmental parameters.

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