Characterization of uncertainty in outdoor sound propagation predictions\textsuperscript{a)

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Abstract: Predictive skill for outdoor sound propagation is assessed using high-resolution atmospheric fields from large-eddy simulations (LES). Propagation calculations through the full LES fields are compared to calculations through subsets of the LES fields that have been processed in typical ways, such as mean vertical profiles and instantaneous vertical profiles synchronized to the sound propagation. It is found that mean sound pressure levels can be predicted with low errors from the mean profiles, except in refractive shadow regions. Prediction of sound pressure levels for short-duration events is much less accurate, with errors of 8–10 dB for near-ground propagation being typical.  

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1. Introduction  
Propagating sound waves are sensitive to complex, four-dimensional details of the atmosphere that cannot be fully resolved with available observation systems. This insufficiency in the data introduces uncertainty into sound propagation predictions. For example, a common situation is to have available wind and temperature data collected at only a few discrete heights on a single, vertical tower, in which case the vertical structure of the atmosphere is coarsely sampled, while the horizontal structure is not directly sampled at all. Additionally, the location where the atmospheric data are collected often does not coincide with the path of sound propagation. Numerical weather forecast data, which are becoming increasingly used, sample all three spatial dimensions and time but at a much lower resolution than needed for accurate predictions. Given the practical compromises involved, it is necessary to assess the skill of propagation predictions for particular types and resolutions of atmospheric inputs.  
The CASES ’99 experiment, described in Ref. 1, illustrates how predictive skill is often limited by the atmospheric data. This experiment demonstrated that, even on a clear night over flat terrain with wind and temperature collected at 5 m increments on a 50 m tower, the timing and location of 5–20 dB fluctuations in sound level could not be consistently predicted.  
This study uses a simulation approach to assess predictive uncertainty for sound propagation at low frequencies. Turbulence simulations are performed at as high a resolution as  

\textsuperscript{a)Preliminary results from this study were presented in D. K. Wilson, E. L. Andreas, J. W. Weatherly, and C. L. Pettit, “Uncertainty in outdoor sound propagation predictions as determined from high-resolution atmospheric simulations,” InterNoise 2006, Honolulu, HI.}
practical to create surrogate atmospheric fields. Sound is then propagated through these fields, and the results are statistically compared to predictions based on less detailed but more typical atmospheric data sets, such as mean vertical profiles and instantaneous vertical profiles at a location near the propagation path.

2. Description of the atmospheric simulations

Our atmospheric simulations of the wind and temperature fields are based on the method of large-eddy simulation (LES), which is commonly applied to high Reynolds number flows such as the atmosphere. The simulations were performed on a parallel-processing supercomputer with 100 CPUs in order to obtain the highest practical resolution. Four different atmospheric density stratifications were simulated; these are termed very unstable, unstable, neutral, and stable. Unstable stratification is characteristic of sunny days, neutral stratification of windy and cloudy conditions, and stable stratification of clear nights. The ground is flat with uniform roughness elements. The important parameters for the four runs are shown in Table 1.

Table 1. Parameters characterizing the four large-eddy simulations used in this study.

<table>
<thead>
<tr>
<th>Stratification</th>
<th>Very unstable</th>
<th>Unstable</th>
<th>Neutral</th>
<th>Stable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Friction velocity (m s(^{-1}))</td>
<td>0.317</td>
<td>0.295</td>
<td>0.219</td>
<td>0.284</td>
</tr>
<tr>
<td>Roughness length (m)</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>0.1</td>
</tr>
<tr>
<td>Sensible heat flux (W m(^{-2}))</td>
<td>115</td>
<td>29</td>
<td>0</td>
<td>-13.3</td>
</tr>
<tr>
<td>Geostrophic wind speed (m s(^{-1}))</td>
<td>5.0</td>
<td>5.0</td>
<td>5.0</td>
<td>8.0</td>
</tr>
<tr>
<td>Boundary-layer height (km)</td>
<td>650</td>
<td>650</td>
<td>615</td>
<td>195</td>
</tr>
<tr>
<td>Dimensions (km)</td>
<td>2.4 x 2.4 x 1</td>
<td>2.4 x 2.4 x 1</td>
<td>2.4 x 2.4 x 1</td>
<td>1 x 1 x 0.4</td>
</tr>
<tr>
<td>Resolution (m)</td>
<td>4 x 4 x 2.5</td>
<td>4 x 4 x 2.5</td>
<td>4 x 4 x 2.5</td>
<td>2 x 2 x 1</td>
</tr>
<tr>
<td>Total duration (s)</td>
<td>983</td>
<td>914</td>
<td>710</td>
<td>653</td>
</tr>
<tr>
<td>Number of saved volumes</td>
<td>200</td>
<td>200</td>
<td>200</td>
<td>120</td>
</tr>
</tbody>
</table>

Mm. 1 and Mm. 2 show vertical cross sections, aligned with the nominal (geostrophic) wind direction, for the very unstable and stable stratification. In unstable stratification, plumes of relatively warm air rise from the heated surface. The air 50 m or so above the surface tends to be well mixed. In stable stratification, wave motions form and there is much less mixing. The animations also show synchronized upwind and downwind sound propagation simulations, which were performed by the method to be described in the next section.

3. Sound propagation calculations and procedure

The sound-propagation calculations were performed with a two-dimensional, wide-angle, Crank-Nicholson, parabolic equation (CNPE) code of the type described by West et al., which is accurate for propagation angles within 20–30° of horizontal. Height- and range-dependent cross sections of the LES fields can be readily incorporated into the CNPE, which takes as input the sound speed (which depends on temperature) and the horizontal wind component in the direction of propagation. The source height in all calculations is set to 1 m, and the ground properties are characteristic of short grass, as described in Ref. 1. Predictions in the nominal
downwind, upwind, and crosswind directions, out to a range of 1 km, were calculated at the frequencies 50, 150, and 250 Hz. CNPE calculations were repeated for each available saved volume (snapshot) from the LES simulations.

In discussing skill of the sound propagation predictions, event and mean predictions are distinguished and separately examined here. A propagation event has short duration compared to the time scales (associated with turbulence, internal waves, etc.) over which the atmosphere substantially modifies the propagation. Event prediction could apply to propagation of an explosion, or to predicting the sound level produced by a steady source over a short duration. Mean prediction involves predicting the ensemble mean-square sound pressure for a particular set of stationary atmospheric forcings. Mean-square sound pressure predictions over time intervals in which the forcings change, such as daily or seasonal intervals, would represent another distinct case for a predictive skill analysis.

Similarly, atmospheric data may be collected and processed on an event (equivalently, snapshot or sample) or mean basis. For example, a single radiosonde (weather balloon) ascent provides a snapshot of the atmosphere along a particular time/space trajectory. Forecasts from numerical weather prediction (NWP) models, on the other hand, typically provide ensemble mean (Reynolds averaged) atmospheric fields. Although it might seem natural that event propagation should be predicted with event atmospheric data and mean propagation predicted with mean atmospheric data, there is no consistent practice for doing so. For example, mean sound levels are often predicted from radiosonde profiles (event data), and NWP results (mean data) have been used to predict propagation of explosions.

In the following, we evaluate the accuracy of event and mean propagation predictions using event and mean atmospheric data. Specifically, we consider the following types of processed atmospheric data:

- **Ensemble-mean vertical profiles**, which are calculated by averaging over horizontal planes in each LES volume, and then over time.

- **Instantaneous, along-path mean vertical profiles**, which are averages of the vertical profiles along the propagation path at the same time as the propagation event. Hence these are spatial, but not temporal, averages.

- **Instantaneous, midpoint vertical profiles** collected at a distance of 500 m from the source along the direction of propagation. When predicting event propagation, they are synchronized to the event. These profiles are at the true midpoint of the propagation path only for the 1000 m receiver distance.

- **Instantaneous, displaced vertical profiles** are the same as the instantaneous, midpoint profiles, except that the collection point is moved an additional 500 m in the direction transverse to the propagation (the positive crosswind direction).

The bias and mean-square errors associated with the various predictions are calculated from, respectively,

$$b = \frac{1}{N} \sum_{i=1}^{N} (\hat{\phi}_i - \phi_i), \quad \sigma^2 = \frac{1}{N} \sum_{i=1}^{N} (\hat{\phi}_i - \phi_i)^2.$$  \hspace{1cm} (1)

Here, $i$ is the index of a particular LES volume snapshot, $N$ is the number of snapshots, $\hat{\phi}_i$ is the value of the estimator associated with that snapshot (namely, the sound level prediction in dB), and $\phi_i$ is the actual value to be estimated, as determined from the fully resolved LES fields. In some cases, the $\hat{\phi}_i$ and/or $\phi_i$ may be the same for all of the snapshots; for example, if biases associated with predictions of the mean sound level are being calculated, the $\hat{\phi}_i$ are all equal to the mean sound level in dB.
4. Results and discussion

4.1 Predictability of mean sound levels

We first consider prediction of mean sound levels from various types of atmospheric inputs. The actual mean levels (the $\phi_i$ in this case, which are the same for all $i$) are calculated by propagating the sound through each fully resolved LES cross section, averaging the mean-square sound pressures, and then converting to dB. Each image in Fig. 1 shows errors associated with a particular type of atmospheric input data, with the left side of each image representing upwind propagation and the right side downwind propagation. All calculations are for 150 Hz and unstable stratification. The upwind propagation exhibits strong, upward refraction. The downwind propagation exhibits weak ducting near the ground and upward refraction higher up. Errors tend to be largest near the ground, probably due to the greater importance of refraction at shallow propagation angles.

When ensemble-mean vertical profiles are used to form the estimate (the $\hat{\phi}_i$, which are the same in this case for all $i$) to the actual mean sound level [Fig. 1(a)], sound levels more than 12 dB too low occur near the ground in the upwind refractive shadow. A smaller underprediction of about 4 dB, which is associated with destructive interference between propagating modes, occurs downwind between approximately 400 and 750 m. These errors are attributable to the absence of turbulent scattering in calculations based solely on mean profiles.

Figure 1(b) shows the bias error for mean-sound-level prediction based on calculating the mean-square sound pressure from the instantaneous, displaced vertical profile in each LES snapshot, averaging, and then converting to dB. An approach similar to this one was suggested by Yokota et al., who estimated mean sound levels by averaging predictions from a number of instantaneous, vertical profiles. In comparison to Fig. 1(a), the bias errors are similar in magnitude but opposite in sign. In effect, this estimation method assumes that the turbulent eddies have a spatial extent much longer than the propagation path, which leads to stronger scattering than actually occurs.

Figures 1(c) and 1(d) show the bias and root-mean-square [rms, $\sigma$ from Eq. (1)] errors associated with estimating the mean sound level from a single random sample of instantaneous,
displaced vertical profiles. That is, event atmospheric data are used to estimate mean sound level and $\phi_i$ is therefore different for each LES snapshot $i$. The bias error is similar to Fig. 1(b), although there is a more pronounced negative bias along the upwind shadow zone boundary. There are very substantial rms errors, of 8 or more dB at distances greater than 400 m for near-ground propagation, in both the upwind and downwind directions.

Figure 2 shows the bias error for estimates of the mean sound level using the ensemble mean vertical profiles. Calculations are shown for all four cases of the stratification, and the receiver height is fixed to 2 m. Under prediction of sound levels is found to be a problem for all stratifications but particularly so for upwind propagation in very unstable stratification, which creates the strongest refractive shadow.

4.2 Predictability of event sound levels

We next consider the accuracy of event sound-level predictions. In compiling the statistics, there is a separate random event (and hence a distinct $\phi_i$) for each LES snapshot. Figure 3 shows rms errors for predictions based on each of the four profile types. All calculations are for 150 Hz and unstable stratification. We see that the along-path mean profiles actually produce the best predictions of event sound levels. They are slightly better than predictions based on the ensemble mean profiles. The predictions become much worse when instantaneous (event) profiles are used; the displaced profiles are only slightly worse than the midpoint ones. Apparently, there is enough fine detail in the atmospheric structure along the propagation path that observations at one location and time are not sufficiently representative to produce accurate predictions of a propagation event occurring at that same time. Typical prediction errors, for receivers near the ground at distances greater than 500 m, are 5–8 dB when using the mean profiles and 8–10 dB when using the instantaneous profiles.

The bias errors corresponding to event predictions are not shown here. For the ensemble-mean predictions, the appearance is highly similar to Fig. 1(a). The along-path mean predictions have a similar pattern, but the bias is reduced to a few dB in the shadow region. The instantaneous profiles produce bias errors essentially the same as Fig. 1(c); that is, the scattering into shadow and interference zones is too strong.

Figure 4 shows the effect of changing frequency. Calculations for downwind propagation in stable stratification, crosswind propagation in neutral stratification, and upwind propagation in unstable stratification are shown. The errors at 50 Hz are comparatively small and increase steadily with range. For downwind propagation in stable stratification, the 150 and 250 Hz cases both saturate at a similar error of about 8 dB. The saturation occurs at a shorter distance for the higher frequency. Although other stratifications are not plotted here, they all have essentially the same behavior in the downwind direction. For the crosswind propagation in
neutral stratification and upwind propagation in unstable stratification, the errors tend to increase without saturation as the distance increases. This behavior is actually observed for all stratifications in the upwind and crosswind directions. The errors are considerably larger, up to about 18 dB, in the upwind direction.

5. Conclusions

This study has explored fundamental limitations in predictive skill for outdoor sound propagation. Such limitations are imposed by imperfect spatial and temporal sampling of the atmo-

![Fig. 3](image1.png)

Fig. 3. (Color online) Root mean square errors for estimates of the event sound pressure levels at 150 Hz in unstable stratification by several different methods. (a) Estimation based on ensemble mean vertical profiles. (b) Estimation based on path-averaged vertical profiles. (c) Estimation based on instantaneous vertical profiles at midpoint of the propagation path. (d) Estimation based on instantaneous vertical profiles displaced from the propagation path.

![Fig. 4](image2.png)

Fig. 4. (Color online) Root mean square errors for estimates of the event sound pressure levels based on instantaneous, displaced vertical profiles. Receiver height is 2 m. Three different frequencies are shown: 50 Hz (top), 150 Hz (middle), 250 Hz (bottom). Solid lines: downwind propagation, stable stratification. Dashed lines: crosswind propagation, neutral stratification. Dotted lines: upwind propagation, unstable stratification.
spheric propagation medium. Of course, other aspects of the outdoor environment not considered here, such as terrain features and ground properties, may also introduce uncertainty into propagation predictions.

Predicting mean sound levels from mean atmospheric profiles results in low errors (typically less than 2 dB), except in shadow and destructive interference zones, where scattering by turbulence is important and sound levels are under predicted. Predictions of mean sound level based on averaging propagation calculations from a large number of vertical profiles samples results in substantial overestimation of levels in shadow zones.

When predicting event propagation, synchronized vertical profiles along the propagation path do not lead to good predictive skill, with errors of 8–10 dB being typical for near-ground propagation. In general, mean atmospheric profiles produce the most accurate predictions of both mean and event sound levels, because they are most representative of typical conditions along the propagation path.

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References and links