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PAPER

Influence of short-term meteorological variations over flat grass-covered ground on noise level fluctuation and application of mean meteorological data to noise prediction

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Abstract: For environmental noise prediction, it is practicable to use meteorological data available from local meteorological observatories. However, these observations have limitations induced by the methods of measuring and data processing. Usually only mean meteorological values averaged over one 10 min period every hour are calculated. To apply these mean meteorological variables to noise propagation appropriately, we need to investigate the characteristics of both acoustic and meteorological parameters within the 10 min period. We made simultaneous measurements of both parameters over flat grass-covered ground and estimated effective sound speed profiles by similarity theory, using the meteorological data measured under conditions similar to those at local observatories. The changes in sound pressure level in periods around sunrise and sunset were similar and were smaller than those around culmination, in which fluctuations of approximately 20 dB were measured at higher frequencies at a distance of 100 m. Noise predictions by the parabolic equation method and sound speed profiles determined from instantaneous meteorological variations generally agreed with the measurements except in the time period around culmination. When we used 10 min mean meteorological values in combination with the parabolic equation method, we obtained reasonable agreement with the measurements at middle frequencies in time periods around sunrise and sunset.

Keywords: Outdoor noise propagation, Noise prediction, Instantaneous meteorology, Parabolic equation method, Similarity theory, Logarithmic approximation

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1. INTRODUCTION

Meteorological conditions strongly affect outdoor sound propagation. A number of reports [1–5] have demonstrated the effects of temperature and wind speed gradients, atmospheric turbulence and other factors above the ground surface. In some of these studies, a meteorological tower or mast was installed at the experimental site, and precise experimental results acquired from the meteorological observations were examined and taken into account in the noise predictions.

Because meteorological observations are made widely for various purposes, we can expect to find such data useful for noise predictions in practical situations. However, these observations have limitations induced by the methods of measuring and data processing. Namely, in most cases, individual meteorological variables are measured at only a single point, and only values averaged over a 10 min period every hour are provided. This suggests that, for noise prediction, further investigations of the effect of meteorological variables measured at local meteorological observatories are necessary.

In this study, we made simultaneous measurements of both meteorological variations and noise propagation over flat grass-covered ground and estimated effective sound speed profiles from similarity theory using meteorological data obtained under conditions similar to those at local observatories. We compared relative sound pressure levels in the measurements with those predicted by combining the parabolic equation method with the instantaneous effective sound speed profiles, and we studied effectiveness applying similarity theory. Thus, we examined the agreement between the measurements and predictions by using the effective sound speed profile estimated by meteorological data averaged over 10 min.

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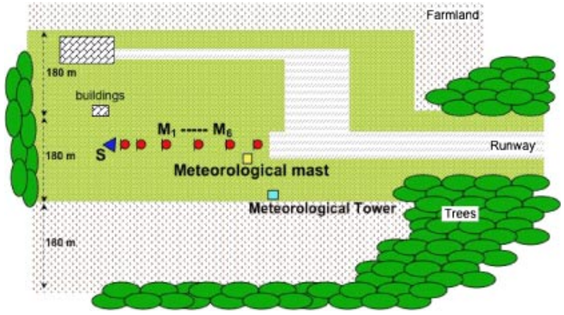


Fig. 1 Schematic illustration of experimental site. S is a loudspeaker, and M_1 to M_6 are six precision sound level meters.

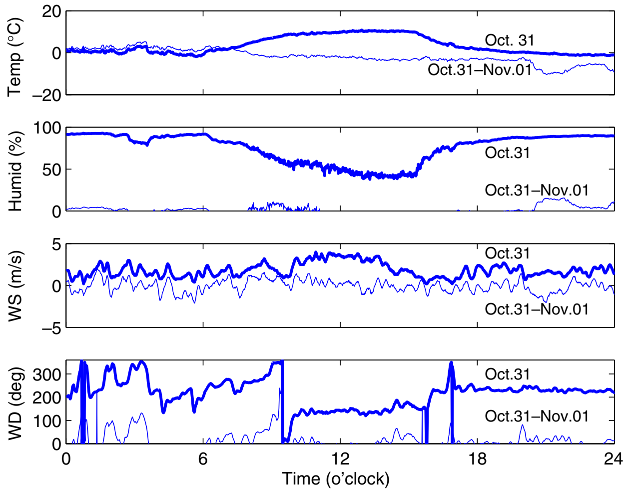


Fig. 2 General meteorological conditions at the experimental site recorded by a meteorological tower. Vertical axes show atmospheric temperature (Temp), relative humidity (Humid), wind speed (WS) and wind direction (WD).

2. EXPERIMENTS

The field experiments were performed above flat grass-covered ground in part of a large public park that was unobstructed by obstacles such as trees and buildings, as shown in Fig. 1, on two sunny days in early winter (31 October and 1 November, 2005).

As a sound source, white noise was emitted from a loudspeaker. The white noise propagating along the ground was received by six precision sound level meters and recorded on a digital audio tape recorder (DAT recorder). The distances between the sound source and the receivers were 6.25, 12.5, 25, 50, 75 and 100 m. The loudspeaker was placed 1.3 m above the ground, and the sound level meters were placed 1.2 m above the ground.

To investigate the vertical profiles of meteorological variables near the ground surface, a meteorological mast was set up close to the sound level meter 100 m away from the sound source (Fig. 1). Three sets of meteorological sensors were mounted on the mast at heights of 1.25, 3.25 and 7.75 m from the ground surface. Each set of sensors consisted of a 2D ultrasonic anemometer and a thermocouple 0.25 mm in diameter. All meteorological measurements were recorded on another DAT recorder, which was synchronized in time with that used for the acoustic measurements.

Acoustic and meteorological measurements were made at three different times of day for about 2 h around sunrise, culmination and sunset on the two days. The times of sunrise, culmination and sunset were approximately 6:09, 11:18 and 16:27, respectively. In each experimental session, white noise was emitted continuously for about 2 h and was measured simultaneously with the meteorological signals.

The recorded acoustic signals were analyzed continuously into 1/3-octave band frequencies by linear averaging for 1 s. Wind speed and direction were sampled every 0.2 s, and the atmospheric temperature was acquired every 0.5 s. After sampling, each meteorological datum was re-averaged over 1 s for comparison with the 1/3-octave band frequency spectrum.

A meteorological tower had been installed originally in the park before the experiments (Fig. 1). A propeller-type anemometer and a thermohygrometer were mounted on the tower at heights of 10 and 2 m above the ground, respectively. Wind speed and direction were outputted every 1 min, and these were the values averaged over 10 min before each data acquisition. Temperature and humidity were measured every 1 min. These data, therefore, reflect general meteorological conditions at the experimental site. Figure 2 is graphs showing the variation of meteorological conditions during the two days. The variables changed steadily and periodically, and the differences between the two days, indicated by thin lines, were small, suggesting that the weather conditions were similar and gentle during the measurement period.

3. RESULTS AND DISCUSSION

3.1. Estimation of Acoustic Impedance and Surface Roughness Length of Grass-Covered Ground

To estimate the acoustic impedance of the ground, where the height of the grass was about 0.05 to 0.07 m, sound pressure levels measured 12.5 m in front of the sound source were compared with theoretical values calculated by using an impedance model proposed by Miki [6]. It was expected that the meteorological effects would be negligible at this distance. Figure 3 compares the measurements with the theoretical values for a flow resistivity of 85 kPa·s·m^{-2}. Although the frequencies of the interference dips almost agreed, there were some differences in the attenuation, especially at around 300 Hz.

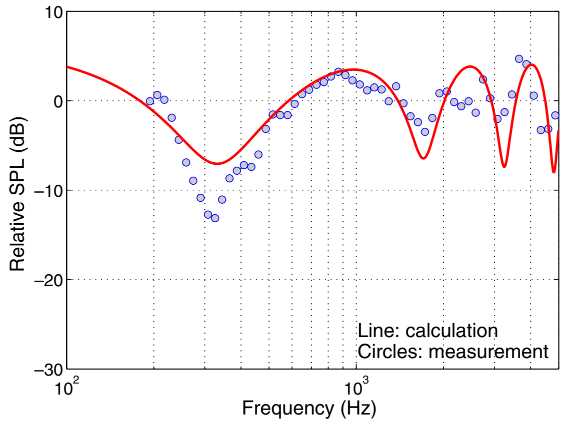


Fig. 3 Estimation of acoustic impedance of grass-covered ground.

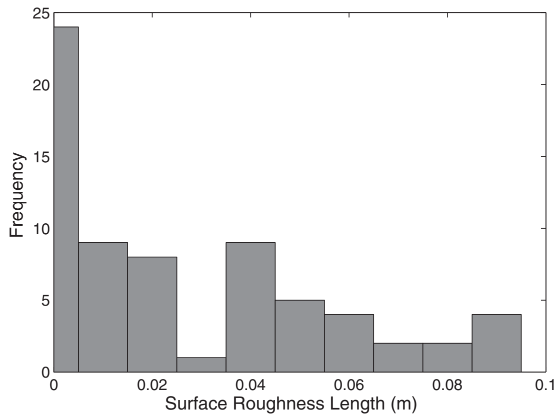


Fig. 4 Distribution of estimated surface roughness length of grass-covered ground.

The model by Miki was a modification of the impedance model for fibrous absorbent materials proposed by Delany and Bazley [7], and both models were developed on the assumption that the materials were isotropic and homogeneous. In this study, since the grass was long and the height was not always the same throughout the experimental field, the insufficiency of applying the model to the grass-covered ground can be suggested. Therefore, discrepancies in the attenuation might be observed.

Surface roughness length [8,9] is one of the parameters essential for estimating meteorological conditions in the surface boundary layer, and is calculated using both data of high wind speeds measured under a neutral atmospheric condition and a logarithmic approximation of the wind speed profiles above the ground. The meteorological conditions were determined from the measurements obtained from the meteorological mast, and the wind speeds above the ground were used to estimate surface roughness length. The estimated surface roughness lengths are shown in Fig. 4 to be distributed widely, and most of them were less than 0.1 m. Although values of less than 0.005 m were the most frequent, those of less than 0.01 m were generally considered as corresponding to reasonably level surfaces in the literatures [8,9]. It is suggested that neither of these values are suitable for the experimental site. On the other hand, the roughness length for long grass has been given as approximately 0.04 m, which is the second most common value in Fig. 4. The high wind speeds under the neutral condition that appeared in our measurements might be still insufficient to allow us to estimate the surface roughness length, which might be the reason for the wide distribution. Considering the site conditions, the surface roughness length of 0.04 m was adopted for our calculations.

3.2. Meteorological Variations Observed Using Meteorological Mast at Experimental Site

Measurements taken from the meteorological mast reflect detailed conditions that are more local and closer to the ground surface than those obtained from the meteorological tower. Figure 5 shows plots of the 1 s variations in atmospheric temperature, wind speed and wind direction over the three different time periods, measured using the meteorological mast. Furthermore, wind speed and direction were used to calculate the wind speed in the direction of sound propagation. From these figures, each time period is characterized as follows.

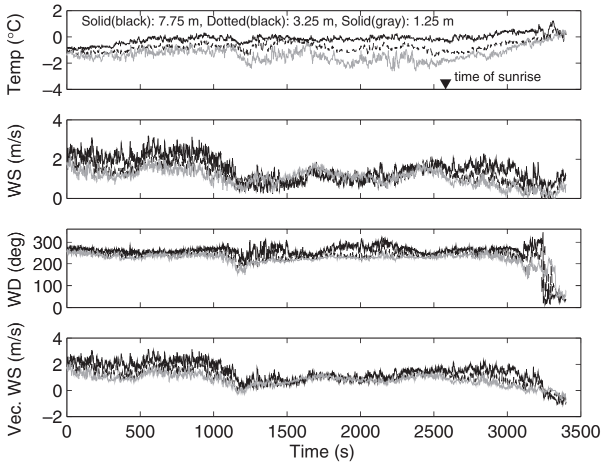
In the time period around sunrise, atmospheric temperature inversion clearly occurred above the ground, and wind speeds were higher with increasing height from the ground. Considering the wind directions, wind speeds in the direction of sound propagation indicated mostly downwind propagation, i.e., the sound speed profiles cause downward refraction.

An atmospheric temperature lapse occurred and continued in the time period around culmination. Wind speeds fluctuated markedly from moment to moment, and wind speeds in the direction of sound propagation indicated mostly upwind propagation. However, the vertical wind-speed gradients were small. Therefore, the sound speed profiles are upwardly refractive, and the large fluctuations of the atmospheric temperature and wind speed suggest a turbulent atmosphere above the ground.

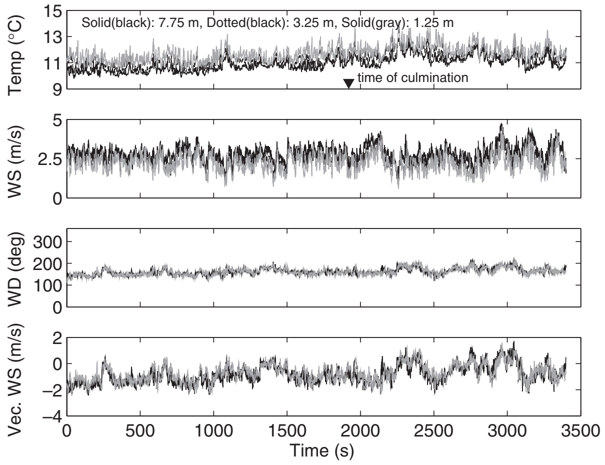
In the time period around sunset, a typical temperature inversion occurred again, and wind speeds were generally higher with increasing height from the ground. Wind speeds in the direction of sound propagation were variable, but exhibited weak downwind propagation as a whole. Most of the sound speed profiles result in downward refraction.

3.3. Instantaneous Changes in Relative Sound Pressure Levels in Measurement

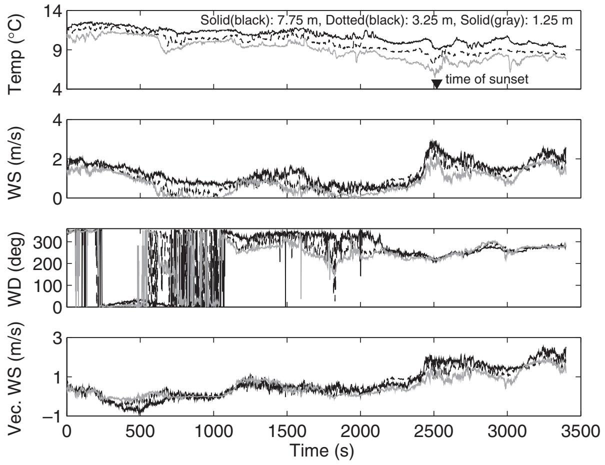
We show changes in sound pressure levels relative to those 1 m in front of the source every 1 s during 10 min in Fig. 6. Furthermore, each 10 min was selected from the time periods indicated in Fig. 5.



(a) 5:26–6:19 on 1 November.



(b) 10:46–11:40 on 1 November.



(c) 15:45–16:39 on 1 November.

Fig. 5 Changes in meteorological variables at three different heights obtained from a meteorological mast. Wind speed in the direction of sound propagation is denoted as Vec. WS and other abbreviations are the same as those in Fig. 2.

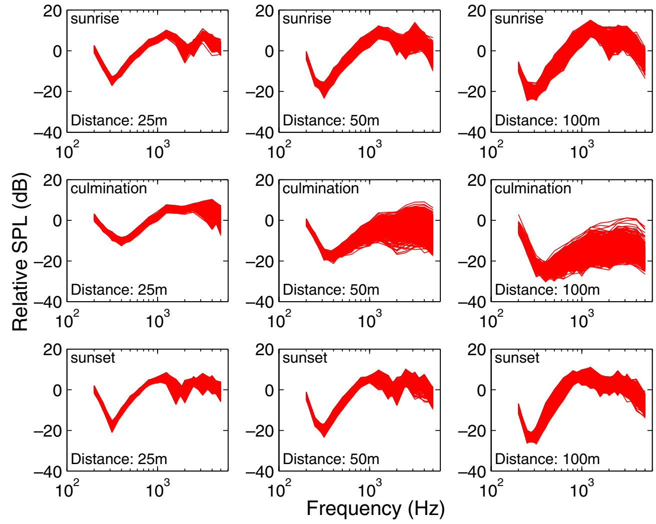


Fig. 6 Changes in relative sound pressure level every 1 s during 10 min in each time period.

In the time period around sunrise, a maximum attenuation of about 20 dB appeared at a frequency of 315 Hz at distance of 25 m, and attenuation decreased gradually toward higher frequencies. Fluctuations of the attenuation during the period were small and were less than 10 dB even at high frequencies. As propagation distance increased, the dip frequency tended to decrease, and the attenuation reached around 25 dB at 100 m. The decrease of the dip frequency may suggest a downwind propagation condition in the time period. The overall tendency of sound attenuation did not change markedly with increasing propagation distance, while the fluctuations of attenuation increased to about 10 dB or more at most frequencies at 100 m.

Attenuation in the time period around culmination was different from that in the other two time periods. Sound attenuated markedly at middle and high frequencies as propagation distance increased. The maximum attenuation at around 400 Hz were about 30 dB at 100 m. While the fluctuations of attenuation at high frequencies were larger than those at other frequencies at 50 m, those at middle frequencies increased to the same degree as high frequencies at 100 m and reached 20 dB or more. Dip frequency tended to increase during the propagation, which may indicate that sound propagates upwind.

The tendency of sound attenuation in the time period around sunset was similar to that around sunrise, although the fluctuations of attenuation were smaller at each distance.

3.4. Estimation of Effective Sound Speed Profiles by Using Surface Layer Similarity Theory

Surface layer similarity theory [8,9] assumes stratified atmospheric layers above the surface in which the atmospheric conditions are stable and uniform, and considers that statistical values of wind speed and atmospheric temperature in the turbulent layers are uniquely determined.

L'Espérance *et al.* [3] compared several method of estimating sound speed profiles above the ground surface and concluded that similarity theory had advantages over the logarithmic method regarding the simplicity of the measurement as well as providing an accurate description of the atmosphere. Stinson and Daigle [4] also compared similarity theory with logarithmic approximation and pointed out several advantages of similarity theory, especially in accuracy. Similarity theory was applied to derive the vertical sound speed profile above the ground in the Harmonoise project [10]. In the light of these findings, we used similarity theory and our instantaneous meteorological measurements to estimate effective sound speed profiles in the three different time periods.

In similarity theory using the scales of frictional velocity u^*, frictional temperature T^* and the Monin-Obukhov length L, the vertical wind speed profile $u(z)$ is described by

$$u(z) = (u^*/\kappa)[\ln(z/z_0) - \Psi_{\rm m}(z/L) + \Psi_{\rm m}(z_0/L)], \quad (1)$$

and the vertical temperature profile $T(z)$ is described by

$$T(z) = T(z_0) + (T^*/\kappa)[\ln(z/z_0) - \Psi_{\rm h}(z/L) + \Psi_{\rm h}(z_0/L)], \quad (2)$$

where $\Psi_{\rm m}$ and $\Psi_{\rm h}$ are universal functions. Here, z is the height from the ground surface and z_0 is the roughness length of the ground surface. κ is the von Karman constant with a value of 0.4. Several different universal functions have been proposed, and we used the Businger-Dyer equations as follows:

$$\Psi_{\rm m} = \begin{cases} \ln[(1+x^2)(1+x)^2/8] \\ -2\cdot\arctan x + \pi/2, & L<0 \\ -5z/L, & L>0 \end{cases} \quad (3)$$

and

$$\Psi_{\rm h} = \begin{cases} 2\ln\left[\frac{1}{2}\left(1+\sqrt{1-16z/L}\right)\right], & L<0 \\ -5z/L, & L>0 \end{cases} \quad (4)$$

where

$$x = (1-16z/L)^{1/4}. \quad (5)$$

The relationship among u^*, T^* and L is

$$\kappa g L T^* = T_{\rm s} u^{*2}, \quad (6)$$

where g is the gravitational acceleration and $T_{\rm s}$ is the ground surface temperature. By using these equations, the effective sound speed profile $c(z)$ in the surface boundary layer can be obtained from

$$c(z) = c_0\sqrt{1+T(z)/273} + u(z)\cos\phi, \quad (7)$$

where c_0 is the sound speed at 0°C and ϕ is the angle between the wind and the direction of sound propagation. In the process of estimating the effective sound speed profiles, we applied an iterative scheme for determining initial estimates of u^* and T^* [3]. We compare measurements of temperature and wind speed in the direction of propagation with the estimations obtained using similarity theory, and an example of a comparison over 1 s is illustrated in Fig. 7. The measured and estimated values agreed well, and thus the estimation of the effective sound speed profile was validated. However, we found a number of instances in which the iterative scheme failed to converge and was consequently not functional since L had a small positive value. This occurred especially in the time periods around sunrise and sunset. L'Espérance *et al.* [3] have already pointed out this phenomenon and have indicated that this mainly occurs as a result of temperature inversion. To improve our calculation procedure, we used the logarithmic approximation instead of similarity theory only in these instances of small positive L.

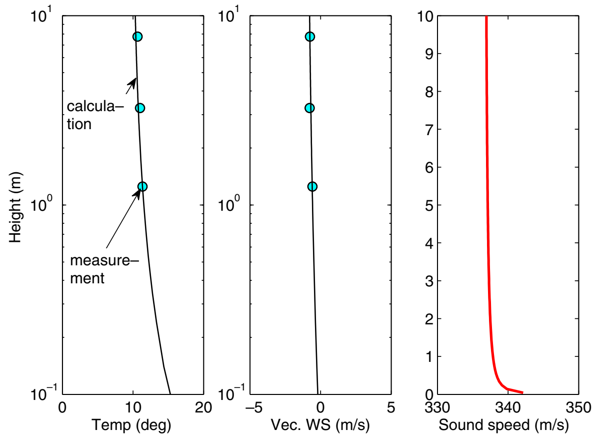


Fig. 7 Comparison between meteorological measurements and estimations by using similarity theory over 1 s, and the calculated effective sound speed profile.

Figure 8 shows effective sound speed profiles every 1 s, estimated from the calculation procedure using similarity theory with instantaneous meteorological data for 60 s in the three different time periods. Examination of the sound speed profiles reveals that propagation around sunrise and sunset was downwardly refracted, whereas propagation around culmination was refracted upwardly. It is also suggested, by consideration of the values of L used in the calculation processes, that the atmosphere was stable around sunrise and sunset, while the atmosphere around culmination was unstable.

3.5. Comparison of Relative Sound Pressure Levels between Measurement and Parabolic Equation (PE) Calculation by Using Instantaneous Effective Sound Speed Profiles

We used the effective sound speed profiles shown in Fig. 8 to compare the measurements of relative sound pressure level with the PE calculation at 500 Hz and 1 kHz

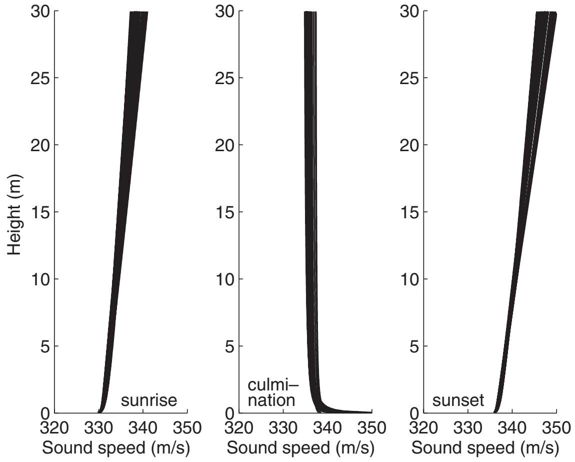


Fig. 8 Effective sound speed profiles estimated from calculation procedure using similarity theory and instantaneous meteorological variables for 60 s.

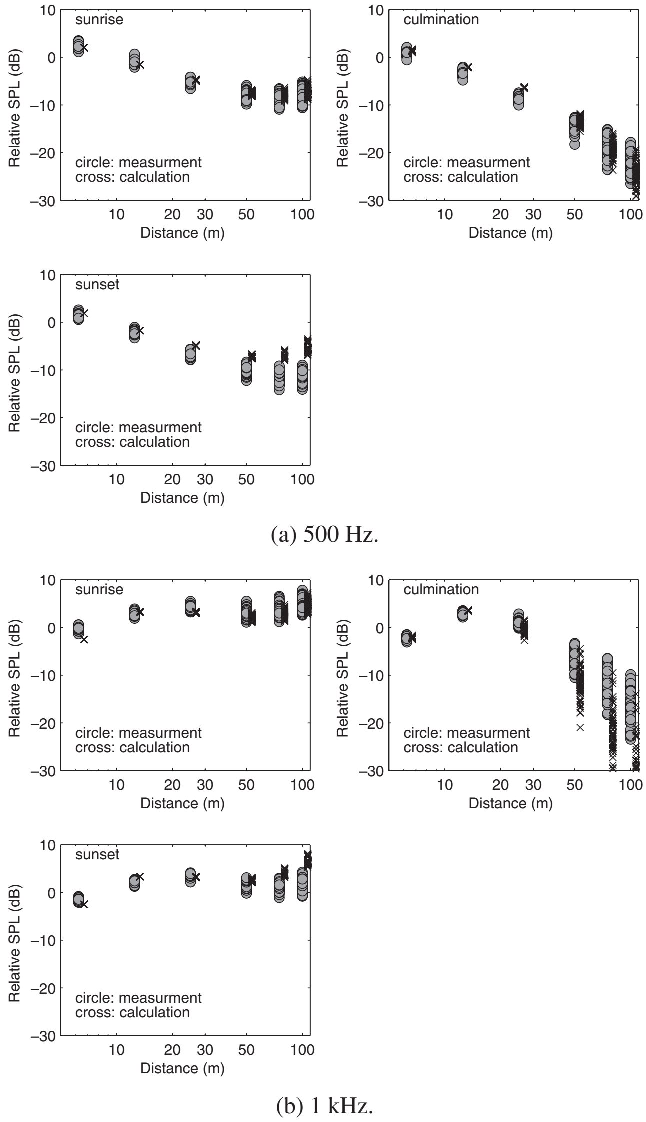


Fig. 9 Comparison of relative sound pressure levels between measurements and PE calculations by using the effective sound speed profiles shown in Fig. 8.

(Fig. 9) [11,12]. In the PE method, a sound field is calculated by solving a PE that follows from a wave equation by introducing some assumptions. The Crank-Nicholson finite difference method or the Green's function is typically used for computing the PE numerically, and in all cases extrapolation of the sound source is repeated stepwise toward the receiver. In the process, not only meteorological effects but also ground surface conditions can be taken into account [12–14]. Here, the PE calculations were carried out for 1/9-octave band center frequencies, and sound pressure levels into 1/3-octave band frequencies were calculated by energy-averaging the levels into 1/9-octave bands.

The relative sound pressure levels measured in the periods around sunrise and sunset were similar at each frequency. The relative levels at 500 Hz decreased gradually with propagation distance up to 50 m, and the levels became almost constant or tended to increase slightly at greater distances. Fluctuations of the relative level in the 60 s were small at the receivers close to the sound source but gradually increased with increasing propagation distance. At 1 kHz, the relative sound pressure levels in the time periods increased generally with increasing distance near the source and appeared to decrease briefly at 50 m, but increased again toward more distant receivers. The degree of fluctuation of the relative level at 1 kHz was similar to that at 500 Hz at each distance. The overall tendency of distance attenuation in the period around culmination was different from that in the other two time periods. The relative levels at 500 Hz continuously decreased with propagation distance. Fluctuations of the relative level became larger at more distant receivers, similarly to the other two periods. However, the degree of fluctuation in the 60 s was larger and reached about 10 dB at 100 m. The relative sound pressure levels at 1 kHz increased briefly at receivers close to the sound source but decreased toward the receivers more distant than 25 m. Fluctuations of the relative level rapidly became larger with increasing the propagation distance. The degree of fluctuation at 1 kHz was about 15 dB at 100 m and was larger than that for 500 Hz.

Overall, the PE calculations showed agreement with the relative sound pressure levels at both frequencies observed in the periods around sunrise and sunset. In addition, they showed, to some extent, similar increases in both the sound pressure level and the degree of fluctuation at more distant receivers. Among the results, we found discrepancies between the measurements and calculations in the period around sunset at more distant receivers. It is supposed that there may have been certain atmospheric factors that could not be reflected in the estimation process of the effective sound speed profile. In the period around culmination, the calculations at 500 Hz were in good agreement with the measurements. Clear differences between the fluctuations of the level obtained by the measurements and calculations appeared at 1 kHz with increasing distance, although the overall trend in noise attenuation was still similar. This difference may have been caused by atmospheric turbulence, since it only appeared at 1 kHz and did not appeared at 500 Hz, and atmospheric turbulence tends to affect high frequencies. For the period around culmination, the measurements for which the Monin-Obukhov lengths were negative, indicating an unstable atmosphere, were much more frequent than those in the other time periods. As sound propagates under upward refraction in a turbulent atmosphere, the sound scattered by the turbulence propagates to some extent into the shadow region [12], and therefore the sound pressure level does not continue decreasing even when propagation distance increases. Namely, the relative sound pressure levels in our calculations might have been increased to some extent by the effect of turbulence. However, the effect could not be examined by the calculation procedure, and the above differences were seen in consequence. Consideration of the effect of turbulence on the effective sound speed profile is a future subject of this study, since it may require detailed analyses of meteorological measurements.

3.6. Application of Mean Meteorological Variables to Noise Propagation Calculation

To apply the meteorological values averaged over 10 min every hour to noise prediction, we need to examine the implications of averaging over 10 min. Relative sound pressure levels obtained from both the PE calculation and the effective sound speed profiles determined from meteorological values obtained from the mast averaged over each 10 min for 1 h in the three different time periods over the two days are shown in Fig. 10.

For the measurements on 31 October, the frequency distributions of the mean relative sound pressure levels over 10 min did not change markedly in each of the three time periods at each distance. For instance, the fluctuations of the relative level were around 5 dB at 50 m and 10 dB or less at 100 m, with some dependence on the frequency. The increase in fluctuation at 100 m may have been because the meteorological effects appeared to be relatively larger at more distant receivers. These tendencies can also be seen from the measurements on 1 November, and the frequency distributions were similar at each propagation distance and each time period over the two days.

The relative sound pressure levels obtained by the measurements and calculations showed agreement, especially at middle frequencies from 500 Hz to 1 kHz at 50 m in the periods around sunrise and sunset on 31 October. However, the fluctuations of the relative level obtained by calculations appeared to be smaller than those obtained by measurements, and little agreement was seen at frequencies of more than about 2 kHz. The differences at around 300 Hz might be due to the insufficiently accurate estimation of the acoustic impedance of the ground. At the distance of 100 m, while the agreement at middle frequencies remained in the two time periods, the differences at high frequencies appeared to increase. The discrepancies in the period around culmination became markedly larger, as the distance increased. Results for the measurements and calculations on 1 November were almost the same as those on 31 October.

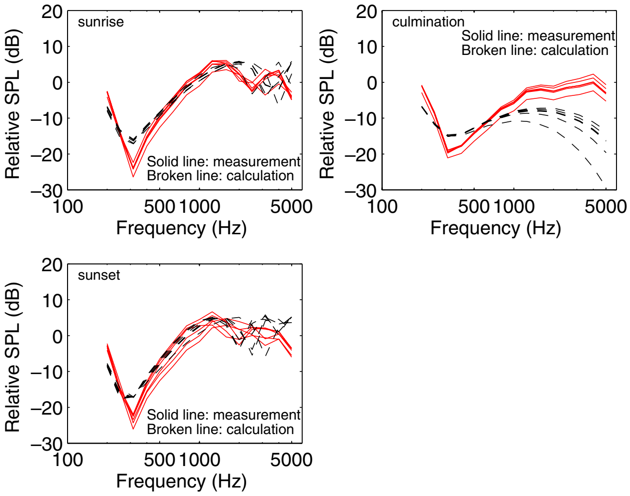
Since the propagation attenuation at high frequencies tended to be easily affected by various factors, the mean meteorological variables averaged over 10 min may be insufficient to obtain reasonable agreements with the measurements at such frequencies. Baume *et al.* [15] examined the correlations between micrometeorology and acoustics, and they noted the importance of averaging intervals to characterize the propagation conditions of sound. Furthermore, the large differences in the period around culmination might have been mostly caused by atmospheric turbulence, and the improvement can be made by considering the effect of turbulence on the sound speed profile in the PE calculations.

Although the discussion on both acoustic and meteorological data averaged over 10 min is based on limited datasets and further investigation is greatly needed, our results indicate the following.

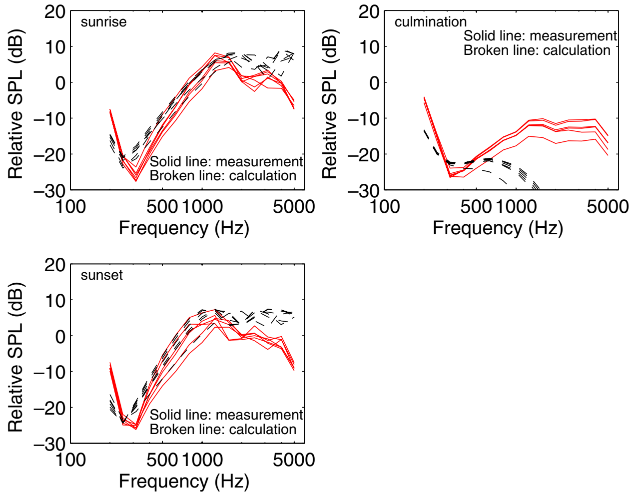
(1) Since the frequency distribution and time variation of the mean relative sound pressure level did not change markedly within 1 h during the measurement period under the gentle weather conditions, we may consider the measured data averaged for 10 min to be typical examples of noise attenuation within the 1 h.
(2) Mean relative sound pressure levels at middle frequencies over 10 min can be estimated from the mean meteorological variables over the same time period except around culmination. This may suggest the feasibility of applying measurements at local meteorological observatories to noise prediction.

4. CONCLUSIONS AND FUTURE WORK

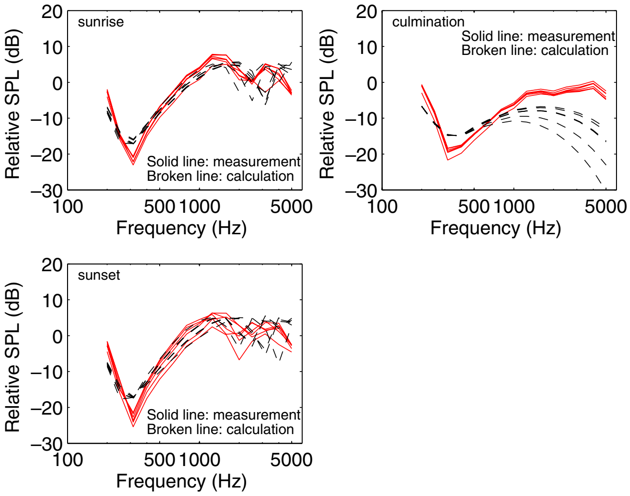
We simultaneously measured noise propagation and vertical meteorological data above flat grass-covered ground on two typical sunny days in early winter. The changes in sound pressure level in the periods around sunrise and sunset were similar and were generally smaller than those around culmination, in which fluctuations of 20 dB or more were measured at high frequencies at a distance of 100 m over 60 s. Sound speed profiles above the ground were generally estimated accurately by using similarity theory and instantaneous meteorological data.



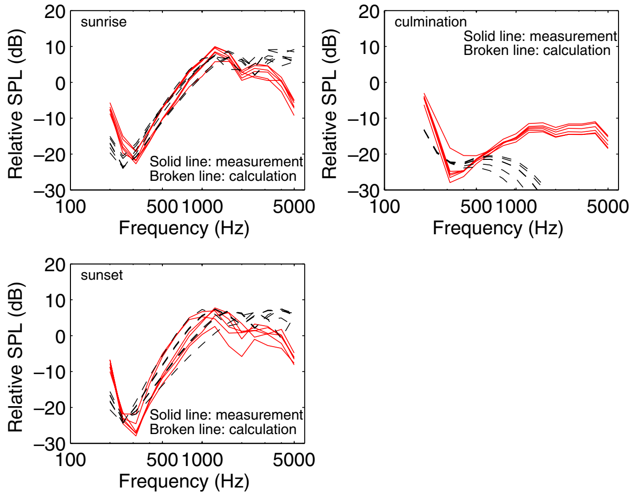
(a) Distance is 50 m (31 October).



(b) Distance is 100 m (31 October).



(c) Distance is 50 m (1 November).



(d) Distance is 100 m (1 November).

Fig. 10 Comparisons of mean relative sound pressure levels over each 10 min for 1 h in measurements and PE calculations.

However, another procedure for calculating the sound speed profile was needed in the cases of atmospheric temperature inversion, which appeared frequently around sunrise and sunset. We used a logarithmic approximation for our calculations at such times. The prediction of relative sound pressure levels from both our estimated instantaneous sound speed profiles and the PE calculation showed reasonable agreement with the measurements, except in the period around culmination. In this time period, atmospheric turbulence appeared to have a strong effect, because of the negative Monin-Obukhov length and the upward refraction. The fluctuations of mean relative sound pressure level over 10 min were around 5 dB at 50 m and 10 dB or less at 100 m throughout the measurements over two days and did not depend markedly on the time period. The relative levels obtained from the PE calculation and the effective sound speed profiles determined from meteorological data averaged over 10 min generally agreed with the measurements at middle frequencies, except around culmination. Thus, discussions on application of measurements at local meteorological observatories may be useful for noise prediction. However, the effect of atmospheric turbulence must be considered in future to resolve the disagreement between measured and calculated results in the period around culmination [12–14].

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