Wind turbine low frequency and infrasound propagation and sound pressure level calculations at dwellings

Stephen E. Keith[a)]
Health Canada, Environmental and Radiation Health Sciences Directorate, Consumer & Clinical Radiation Protection Bureau, Non Ionizing Radiation Physical Sciences Division, 775 Brookfield Road, Ottawa, Ontario K1A 1C1, Canada

Gilles A. Daigle and Michael R. Stinson
MG Acoustics, 5490 Piperville Road, Carlsbad Springs, Ontario K0A 1K0, Canada

(Received 19 April 2018; revised 5 July 2018; accepted 5 August 2018; published online 27 August 2018)

This study was developed to estimate wind turbine low frequency and infrasound levels at 1238 dwellings in Health Canada's Community Noise and Health Study. In field measurements, spectral peaks were identifiable for distances up to 10 km away from wind turbines at frequencies from 0.5 to 70 Hz. These measurements, combined with onsite meteorology, were in agreement with calculations using Parabolic Equation (PE) and Fast Field Program (FFP). Since onsite meteorology was not available for the Health Canada study, PE and FFP calculations used Harmonoise weather classes and field measurements of wind turbine infrasound to estimate yearly averaged sound pressure levels. For comparison, infrasound propagation was also estimated using ISO 9613-2 (1996) calculations for 63 Hz. In the Health Canada study, to a distance of 4.5 km, long term average FFP calculations were highly correlated with the ISO based calculations. This suggests that ISO 9613-2 (1996) could be an effective screening method. Both measurements and FFP calculations showed that beyond 1 km, ISO based calculations could underestimate sound pressure levels. FFP calculations would be recommended for large distances, when there are large numbers of wind turbines, or when investigating specific meteorological classes. https://doi.org/10.1121/1.5051331

[RDC] Pages: 981–996

I. INTRODUCTION

Infrasound produced by wind turbines can be comparable to natural infrasound (Turnbull *et al.*, 2012). Natural infrasound is typically dominated by long range pressure fluctuations from the ocean (microbaroms), short range pressure fluctuations due to local winds and eddies (Bowman *et al.*, 2005; Garces and Willis, 2006), or from surf (Garces *et al.*, 2003). Under certain circumstances wind turbine noise has the potential to exceed natural infrasound, making them a potential source of contamination to low frequency monitoring stations for the Nuclear Comprehensive Test Ban Treaty (see, e.g., Styles *et al.*, 2005; Edwards, 2015; Marcillo *et al.*, 2015).

Under specific conditions, wind turbine infrasound noise has been measured during stable, or very stable atmospheric conditions (e.g., during a temperature inversion at night) at distances of 4 km (Hansen *et al.*, 2015; Zajamšek *et al.*, 2016) and up to 90 km (Marcillo *et al.*, 2015). Observations have also been made during high winds in the daytime to a distance of 20 km downwind (Willshire, 1985; Willshire and Zorumski, 1987; Hubbard and Shepherd, 1991). There are also a number of observations of favorable propagation (i.e., less attenuation, or the sound energy is channeled so that there is a longer distance propagation) of wind turbine noise over water (e.g., Sondergaard and Plovsing, 2005; Boue, 2007; Johansson, 2003). Propagation over even longer ranges (up to 2000 km) has been measured using explosive detonations as sound sources; empirical results (Whitaker, 1995) and Parabolic Equation (PE) simulation (Le Pichon *et al.*, 2012) have shown that infrasound pressure levels from such sources involve mechanisms (e.g., stratospheric ducting and wind perturbations) that are not important for the distances that wind turbine noise propagates.

The previously indicated studies suggest that there may be some cases with sustained propagation that is more favorable than spherical spreading (a 6 dB decrease per doubling of distance) over land. This is not a common option in most commercially available sound propagation models, which were primarily developed for A weighted sound pressure level (SPL) from low sources (like vehicles), and for short propagation distances (up to 1 km). For example, the propagation in ISO 9613-2 (1996) assumes a 6 dB decrease per doubling of distance, although ground attenuation can add up to 3 dB to the levels at 63 Hz at long distances. The standard implementation of Harmonoise also does not provide for sustained propagation more favorable than a 6 dB decrease per doubling of distance; it does include localized SPL increases due to focusing of multiple ground rays, but it restricts each ray to a single ground reflection (van Maercke and Defrance, 2007; Jónsson and Jacobsen, 2008; Salomons *et al.*, 2011). There are methods that allow results that may be comparable to a 3 dB decrease in SPL per doubling of distance (i.e., cylindrical spreading): The Swedish calculation method (SEPA, 2012), but only for conditions over water; and Nord2000 (Plovsing, 2006a,b)

[a)]Electronic mail: stephen.keith@canada.ca

which can be modified to allow coherent summation of multiple reflections (Hidaka *et al.*, 1985; L'Espérance *et al.*, 1992; Sondergaard and Plovsing, 2005).

The most sophisticated common commercially available propagation software use Nord2000 and the Harmonoise P2P models. These models use a simplification where a linear sound speed profile is assumed. In these models, sound speed profiles can be computed with weather classes based on common publically available weather forecasts of wind speed and cloud cover data (Eurasto, 2006; Heimann *et al.*, 2007). For the Harmonoise project, between 100 and 630 Hz, at 1000 m, it was found that an accuracy of 2 dB with 90% probability could be obtained using 25 weather classes based on linear sound speed profiles (Heimann and Salomons, 2004). The simplifications used in these models have been validated at audible frequencies, but their validity at infrasound frequencies has not yet been established.

More powerful computational models such as the PE and the Fast Field Program (FFP) are based on numerical solutions to the wave equation. These methods can accommodate arbitrary sound speed profiles at all frequencies relevant for wind turbines (e.g., 0.5 Hz to 10 kHz), and have been used to predict and explain the long distance propagation from wind turbines (Johansson, 2003; Marcillo *et al.*, 2015).

As part of Health Canada's study (Keith *et al.*, 2016a), yearlong measurements of wind turbine SPL below 70 Hz were compared to FFP and PE calculation methods for a distance up to 10 km (Daigle and Stinson, 2014; Edwards, 2015). To obtain a realistic estimate of the effect of FFP propagation calculations, measurements of wind turbine sound power were used with different calculation methods to obtain outdoor SPLs at dwelling locations from the Health Canada study.

II. METHODS

A. Site descriptions

Field tests of propagation over distances up to 10 km were made in the Canadian maritime province of Prince Edward Island (PEI). The PEI site was 200 km from the Atlantic Ocean and 20 km from the Gulf of Saint Lawrence (a semi-enclosed sea connected to the Atlantic Ocean). SPL calculations at dwellings were made in both PEI, and the inland province of Ontario. The two study areas had a moderate humid continental climate (southern to mid-boreal Dfb Koppen Geiger classification), flat rural agricultural areas with treed wind breaks on fence lines between fields, and occasional small settlements or copses of trees. In both locations the prevailing wind direction was generally from the west, and most locations were less than 15 km north or south of a large body of water (lake, strait, or sea).

B. Locations of dwellings used for calculation of outdoor SPL

The SPL from 399 wind turbines were calculated at the 1238 dwelling locations in the two provinces in the Health Canada study (Keith *et al.*, 2016a; Michaud *et al.*, 2016). Health Canada targeted all dwellings pre-identified within 600 m of any wind turbine in the study area and used a random selection of dwellings at larger distances out to 10 km. Half of the dwellings included in the study were within 1 km of a wind turbine. Within each province, 70 km was the maximum separation between any two turbines included in the study.

C. Weather statistics

In the Health Canada study area weather data were obtained from six weather stations (Environment Canada, 2016; Fisheries and Oceans Canada, 2016). These stations were chosen because they were the only ones within 200 km of a wind turbine that provided cloud cover data.

In the province of Ontario weather data were obtained from the Windsor airport with additional data from the London airport. The PEI weather data were obtained from the Charlottetown airport, with additional data from Nova Scotia at the Halifax airport, and from New Brunswick at the Bathurst and Moncton airports. The latter four stations reported cloud cover with an adjectival descriptive scale (i.e., Cloudy, Mostly Cloudy, Mainly Clear, and Clear), as well as cloud cover in 10% increments. The two Ontario stations only reported using the adjectival descriptive scale. For comparison, data were also obtained from Montreal, Quebec (1000 km away from the Ontario study area), as this was the nearest inland station that had cloud cover in percent. For the wind turbines (and dwellings) in the Health Canada study the nearest weather station was typically located at a distance of 56(29) km [where the number in parentheses is the standard deviation referred to the corresponding last digits of the quoted result per ISO/IEC Guide 98-3 (2008)]. Meteorology from the single nearest weather station was used to estimate wind turbine SPL. The statistics of the data from the other six weather stations were used to estimate uncertainty in weather data. Wind direction was binned in 10° increments.

D. TL calculation

Calculations were based on transmission loss (TL) as defined by the following formula:

$$\mathrm{TL} = -20\log\frac{\text{total acoustic pressure at fieldpoint at ground level}}{\text{acoustic pressure of direct sound field at 1 m from the source}}. \tag{1}$$

The TL as a function of distance at 1.6 Hz and above was calculated using a full wave FFP (Raspet *et al.*, 1985; Lee *et al.*, 1986; Attenborough *et al.*, 1995; Daigle and Stinson, 2014, 2016). The PE method was used at 0.5 Hz

(Gilbert and Di, 1993). All calculations assumed an equivalent point source (Makarewicz, 2011) at a height of 80 m obtained from data measured at close range and a receiver height of 0.01 m.

In the TL calculations, sound speed profiles as a function of height were estimated from similarity theory (Monin and Obukhov, 1954; L'Esperance *et al.*, 1993; Daigle and Stinson, 2014; supplemental material from Keith *et al.*, 2016b). As described later, these data were extrapolated either using onsite weather data (for detailed checking of calculations), or based on the 25 general meteorological classes defined in Harmonoise (Table I).

Typical applications using similarity theory or the Harmonoise meteorological classes do not require profiles for heights above 100–200 m since the propagation distances being considered are typically less than 1 km. Thus in some cases (i.e., Harmonoise classes W2S1, W3S1, W4S1, and W3S2) at heights above 100 m, extrapolation of the low altitude data on which similarity theory is based led to artefacts in the calculation of sound speed as a function of altitude, e.g., the wind would reverse direction. In some cases the temperature would also increase to unrealistic values. For these cases only the profile below 100–200 m was important so that it was not necessary to modify the profiles.

Detailed FFP calculations based on on-site weather station data used terrain elevation obtained from the Geobase dataset (GeoBase Canadian Digital Elevation Data 1945 2010, 2010) with 1 m vertical resolution which was down sampled to obtain a grid with 3 arc min horizontal resolution (i.e., 92 m resolution north–south and 64 m resolution east–west). In the study areas, the ground was essentially flat and this simplification was used for general TL calculations based on generic Harmonoise classes. In all cases the ground impedance was based on uncultivated farm land.

E. Use of ISO standards to obtain generic TL

For comparison with other calculations, the ISO 9613-2 (1996) TL calculations were extended to lower frequencies. For simplicity, the TL in octave bands from 0.5 to 32 Hz was assumed to have the same TL as calculated at 63 Hz using ISO 9613-2 (1996). This is expedient for the purpose of comparison with other calculations; at 63 Hz the ground absorption in ISO 9613-2 (1996) is reflecting for both hard and soft ground, and this situation would not be expected to change for frequencies below 63 Hz. In addition, the ground in the area of the Health Canada study was flat and free of large obstructions.

TABLE I. Wind speed and stability classes that in combination form the 25 Harmonoise weather classes. (a) Wind speed classes W1 to W5 for wind speeds at 10 m height; (b) stability classes S1 to S5 based on cloud cover and time of day.

(a)		(b)		
Wind speed	Wind class	Time of day	Cloud cover	Stability class
0–1 m/s	W1	daytime	0/8 to 2/8	S1
1–3	W2	daytime	3/8 to 5/8	S2
3–6	W3	daytime	6/8 to 8/8	S3
6–10	W4	night	5/8 to 8/8	S4
>10	W5	night	0/8 to 4/8	S5

All ISO 9613-2 (1996) calculations were made at 4 m height due to considerations related to higher frequencies. Although the standard is commonly used for wind turbines, it was not originally intended for mean source and receiver heights greater than 30 m. When the standard is used to calculate ground attenuation at the receiver position, only the distance to the source and the receiver height are considered, and the source height is ignored. The calculations implicitly associate low receiver heights with sound rays near grazing incidence to the ground. ISO 9613-2 (1996) overestimates the known ground attenuation by as much as 15 dB at 0 m height and 500 Hz. This overestimate drops to near 0 dB at 4 m height. At 63 Hz the ISO 9613-2 (1996) calculations are almost independent of height and ground type, so for consistency, calculations at 4 m receiver height were used for all frequencies.

The ISO A-weighted calculations were not performed if the wind turbine to dwelling separation exceeded 10 km, this created a large uncertainty in the ISO calculations when the nearest wind turbine was at a distance close to 10 km (i.e., the wind park associated with the nearest wind turbine could be excluded from calculations). To reduce this uncertainty, calculations were limited to dwellings within 4.5 km of the nearest turbine. This excluded 54 of the 1238 dwellings in the Health Canada study.

In calculations, the time at each wind speed was used to calculate the wind turbine source sound power, and the resulting long term average levels at dwellings. Weather class was not a factor in the TL calculations using ISO standards, and as is common in environmental assessments, the meteorological correction for wind direction (ISO 9613-2, 1996) was not included in the initial calculations.

F. Field measurement validation of FFP and PE TL calculations

TL calculations were validated by field measurements acquired over a 13 month period near Summerside PEI (detailed description in Daigle and Stinson, 2014; Edwards, 2015; Keith *et al.*, 2016a). On this site were four 3 MW Vestas V90 wind turbines (Vestas Wind Systems A/S, Aarhus, Denmark), which were located 40 km from the next nearest wind turbines.

Meteorology for these field measurements, including temperature, humidity, pressure, wind speed, and wind direction, was measured with two Vaisala WXT-520 weather transmitters (Vaisala Corp., Helsinki, Finland) mounted at heights of 2 and 10 m on a guyed aluminum frame tower 2.5 km east (downwind relative to the prevailing wind direction) of the wind turbines. Output data were transmitted and remotely monitored using two Avisaro RS232 Dataloggers (Avisaro AG, Hannover, Germany).

SPLs were obtained at four distances, 125, 2.5, 5, and 10 km from the wind turbines using Chaparral Physics model-25 microbarometers (Chapparal Physics, Fairbanks, AK). At the 125 m distance the microbarometer sensors were within 2 m of the transducers used to measure wind turbine

sound power (Sec. II G). For isolation from wind noise the microbarometer was mounted inside a 0.5 m diameter × 0.9 m high polyvinyl chloride plenum attached to four 15 m long, 1.9 cm outside diameter garden soaker hoses, which extended radially in 4 directions to form an orthogonal "X" shape. Data were recorded using a Nanometrics Trident 24 bit digitizer (Nanometrics, Ottawa, Canada) with a 200 Hz sample rate. These SPL measurements were made at ground level, matching the height used for FFP TL calculations.

In post processing signal enhancement of the sound pressure data used MATLAB (MathWorks, Natick, MA) software for power spectral density employing a "Welch" estimator (50% overlap) and a "Hamming window" with 8192 sample segment length, typically with a 1 h analysis sample time. Under target meteorological conditions, the data were examined at a 2.5 km distance for wind turbine spectral peaks, e.g., harmonics or other broadband spectral peaks. If spectral peaks were found, SPL data from other microbarometer locations were examined as well.

G. Field measurement of wind turbine sound power

Four day field measurements of sound power were performed on ten representative wind turbine models from areas in the Health Canada study (Keith *et al.*, 2016a). This included three wind turbine models in PEI and seven models in Ontario. Measurements followed the methodology to determine the apparent sound power levels from IEC 61400-11 (2012). These procedures were extended to the 0.5 Hz 1/3 octave frequency band. The microphone frequency response below 6 Hz was corrected based on manufacturer data included with the microphones. Microphones were set up at a distance of 60 to 125 m from the wind turbine base, depending on turbine height. As per IEC 61400-11 (2012), Bruel & Kjaer type 4165 microphones (Brüel & Kjær Sound & Vibration Measurement A/S, Nærum, Denmark) were mounted on a ground board with a 95 mm diameter hemispherical foam primary windscreen and a 750 mm hemispherical polyester cloth secondary windscreen (Keith *et al.*, 2016b).

Measurements were obtained over a range of downwind angles, but only measurements in the downwind direction were used to estimate wind turbine sound power. Wind turbines are approximately omnidirectional; the data of Friman (2011), Okada *et al.* (2016), and Buck *et al.* (2018) suggest the directivity index is less than 2 dB and that there is a 5 dB null in the crosswind direction.

For comparison, a soaker hose windscreen similar to those described in Sec. II F for long term measurements was also used; Bruel & Kjaer type 4165 microphones were mounted at the intersection of four 15 m long 3/4 in. diameter soaker hoses extending radially in 4 directions to form an orthogonal X shape. These data were simultaneously analyzed in 10 s time steps using 1/3 octave bands, and with narrowband fast Fourier transform (FFT), using Bruel & Kjaer PULSE V17 software. The FFT used 1600 lines resolution, a 100 Hz frequency span, a "Kaiser Bessel window," and 3 linear averages with 66.7% overlap.

As described in Keith *et al.* (2016b) a weather station was set up 1.5 to 2 rotor diameters from each turbine base to measure wind speed, direction (Sutron Windsonic ultrasonic sensors 5600-0215, Sutron, Sterling, VA), and temperature (Sutron platinum probes with radiation shields 5600-0025) at 2 m and 10 m heights in 1 s intervals. Humidity (Sutron 5600-0312), and wetness (Sutron Decagon dielectric leaf wetness sensor) were also recorded at the 2 m height. Based on Monin-Obukhov similarity theory (Monin and Obukhov, 1954; L'Esperance *et al.*, 1993; Daigle and Stinson, 2014; supplemental material from Keith *et al.*, 2016b) these data were used to estimate wind speed at the nacelle height. Seven of the ten wind turbine models also had years of historical data available from the wind turbine nacelle for wind speed, yaw direction, electrical power output, and rotor rpm in 10 min intervals.

To improve the data quality of measurements made following IEC 61400-11 (2012) it was assumed that wind noise was not significant when the IEC 61400-11 (2012) wind screened measurements and adjacent soaker hose measurements agreed within 1 dB when averaged over the fundamental and first ten harmonics. For IEC windscreen FFT data meeting this criterion, the difference between the average peak dB level of the harmonics was compared to the average level of the noise at the mid frequency between adjacent peaks. This was used to create a criterion for IEC wind screened microphones when soaker hose windscreen data were not available. Additional criteria used to exclude measurements were rain, or gusts (i.e., changes between two sequential wind speed measurements greater than 1 m/s). Spectra were also rejected if the 10 s estimate of rpm was more than a factor of 1.8 lower than that in the corresponding 10 min average measured at the wind turbine nacelle (when available). In addition, for the data at 8 m/s wind speed, all audible noises were validated by listening to the recordings (Keith *et al.*, 2016b).

H. Use of TL to calculate SPL at dwellings

Detailed on-site meteorological data were not available at most dwellings in the Health Canada study, and realistic yearly average SPL estimates at each dwelling were calculated similar to Eurasto (2006) using the 25 Harmonoise weather classes (5 wind speeds and 5 stability classes), and 36 wind directions. Meteorology was based on statistics for the Health Canada study area (Sec. II C). For each wind direction, the FFP and PE TL (see Secs. II D and II E for modeling parameters) based on weather classes was used with the measured wind turbine sound power (Sec. II G) to estimate the SPL at each dwelling. Each of the 1238 dwelling locations included a summation of the sound energy propagating from each of the 399 wind turbines in the Health Canada study.

FFP or PE was used to calculate TL (Secs. II D and II E for modeling parameters) using generic sound speed profiles based on the 25 weather classes from Harmonoise (Heimann *et al.*, 2007) (Table I). The TL was calculated over a grid 20 km downwind and 5 km upwind with 26 m resolution. The grid spanned 20 km in each crosswind direction with 64 m resolution. Bilinear interpolation was used to estimate TL as a function of distance and direction. To reduce spatial fluctuations in the data, the grid data were smoothed using

energy equivalent averaging over a sliding range, ±10% of the radius and ±5° in bearing angle (in practice, long term operational and meteorological changes would also be expected to smooth this fine structure). Due to turbulence upwind in the shadow zone, levels were not expected to drop more than about 20–30 dB relative to inverse square law (Di and Daigle, 1994). As a result, for distances upwind greater than 5 km, the results at 5 km were extrapolated to a larger distance using the inverse square law.

Based on the readily observable spectral peaks in preliminary wind turbine data, TL data were originally calculated at five frequencies 0.5, 1.6, 4.8, 20, and 70 Hz. Calculations in octave bands used the TL data at the nearest frequency by geometric ratio. At and above 50 Hz atmospheric absorption was estimated from ISO 9613-1 (1993) for a temperature of 10 °C and relative humidity of 70%. Atmospheric absorption at lower frequencies was based on data from Sutherland and Bass (2004, 2006).

The calculations were also repeated in the frequency range from 0.5 to 63 Hz, using TL calculated by extending ISO 9613-2 (1996) to lower frequencies (Sec. II E). The FFP TL was not calculated at frequencies relevant for A-weighted levels. However, since most wind turbine installations are evaluated using A-weighting, the current infrasound and low frequency results were compared to overall broadband ISO 9613-2 (1996) A-weighted calculations from Keith *et al.* (2016a). These last calculations were based on the same set of residences and for turbines within 10 km of each of the residences.

III. RESULTS AND DISCUSSION

A. Weather statistics

Figure 1 shows the relative time per day associated with each Harmonoise meteorological class for data averaged over one year. In this section the data for the seven weather stations in the Health Canada study area are combined to simplify presentation of the data. As indicated earlier, in calculations at dwellings, data from the single nearest weather station were used.

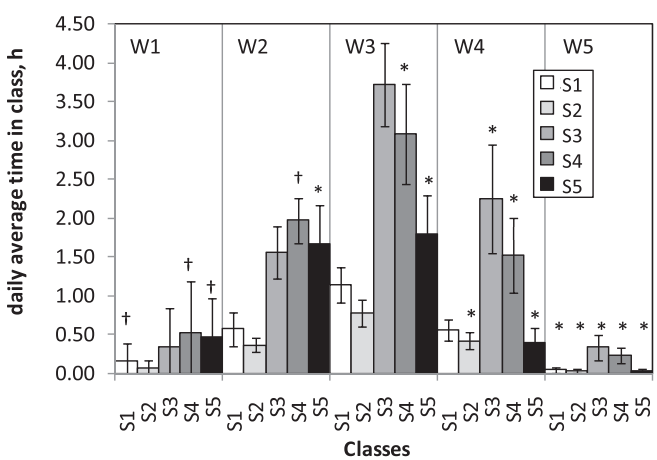

FIG. 1. Annual average occurrence, relative to one day, of the 25 Harmonoise weather classes in the Health Canada study areas. Bars show the average time (in hours) in each class for the seven stations where data were available, and the whiskers represent one standard deviation of these data. The bars sum to 24 h. Asterisks and daggers indicate conditions where propagation at some frequencies below 70 Hz is at least 3 dB more favorable than predicted by ISO 9613-2 (1996). Daggers also indicate low wind speeds that are generally below the wind turbine cut-in wind speeds.

In Fig. 1 only wind speed classes W3, W4, and W5 are typically associated with wind turbine operation as W1 and W2 are generally below the wind turbine cut in speed. In this figure the classes marked by asterisks show that favorable long distance wind turbine noise propagation is most commonly associated with the nighttime (S4 and S5). Wind turbines can potentially operate for 8.7 of the nighttime hours (i.e., 75% of the time between sunrise and sunset) when the wind speed is above 3 m/s cut-in wind speed (i.e., wind classes above 3 m/s such as W3, W4, W5, and W2S5). Weather statistics show that wind typically blows 32% of the time in the prevailing wind direction (±30°), and for any other compass direction (±30°) approximately 14% of the time. Based on the wind direction statistics and Fig. 1, on average a wind turbine is operating 8.7 of the 11.7 nighttime hours (between sunset and sunrise) and relative to that turbine, favorable downwind propagation (±30°) occurs on average 2.8 h for dwellings in the prevailing wind direction and for 1.2 h for other dwellings.

During the daytime hours (classes S1, S2, and S3), classes marked with asterisks and daggers in Fig. 1 show that the most favorable propagation conditions only occur for 2.8 h, and that is almost exclusively during conditions with wind speeds W4 and W5. Combining this with wind direction statistics, favorable propagation of operational wind turbine noise is found to occur on average 0.9 h for dwellings in the prevailing wind direction and for 0.4 h for other dwellings.

B. TL calculation

Figure 2 shows a sample surface plot of the TL for the generic class W3S5. In this plot the region above −65 dB (in red, near 5 km Easting) shows TL near the wind turbine that is associated with a 6 dB decrease per doubling of distance, and toward the right this starts to approach 3 dB decrease per doubling of distance. The red region forms a distorted ellipse showing that this change in propagation is a function of the

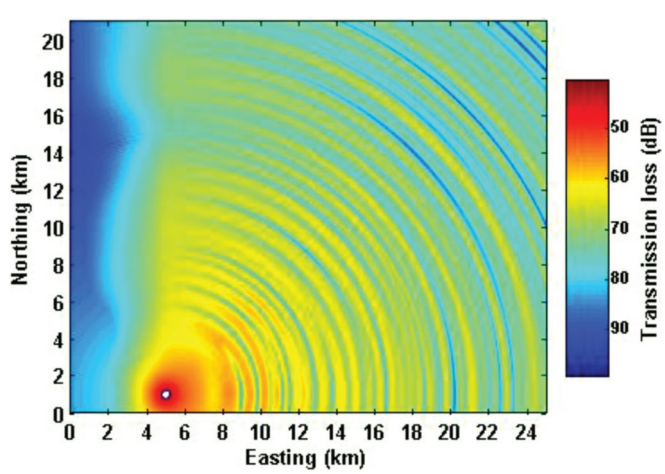

FIG. 2. Surface plot of TL for meteorological class W3S5 at 4.8 Hz as a function of distance, Northing and Easting, from an 80 m high point source (located at 1 km Northing, and 5 km Easting). The wind direction is from the west (left-hand side of plot).

wind angle relative to downwind. At larger distances favorable propagation averaging a 3 dB decrease in SPL per doubling of distance occurs over a range of angles of approximately ±60° relative to the downwind direction. In these areas, there are large fluctuations in the calculated TL due to constructive and destructive interference (with a range of over 20 dB). These fluctuations are consistent with the results of Zajamšek *et al.* (2016) who also found the variation between minimum and maximum measured levels on the order of 20 dB.

Figure 3 shows smoothed data for frequencies from 1.6 to 500 Hz for the meteorological class W1S5, which along with downwind propagation in W2S5 or W3S5 are associated with the most favorable propagation of all classes. This figure takes into account geometrical spreading, ground reflection, ground impedance, and refraction in the case of the FFP. However, the figure excludes atmospheric absorption. The data have been plotted as the difference from results which would be obtained assuming a coherent +6 dB ground reflection, and a 6 dB decrease in SPL per doubling of distance.

Figure 3(a) shows the change in SPL downwind as a function of distance when calculated using generic FFP based on Harmonoise weather class W1S5. The spatial smoothing (averaging) of the data in this figure was found to have little effect at 1.6 Hz, but reduced the spatial fluctuations as much as 20 dB at higher frequencies. It should be noted that the sound speed profile used for calculations was not a function of frequency, so that the path of the sound rays is the same at all frequencies. For distances less than 1.7 km, the data for all frequencies tends toward horizontal lines which indicate a 6 dB decrease in SPL per doubling of distance. At higher frequency above 70 Hz, these curves are shifted down due to ground attenuation, and at 20 km the 500 Hz TL approaches a 9 dB drop per doubling of distance. All curves show some distances where SPL would be higher than expected with a 6 dB decrease in SPL per doubling of distance. Seventy Hz is the highest frequency where the data might arguably approach a 3 dB decrease in SPL per doubling of distance. For 70, 125, and 250 Hz, at a 1.7 km distance there is an observed jump of a few dB in TL, where multiple rays converge to increase the SPL.

Not shown in Fig. 3, the PE calculations at 0.5 Hz show that to a distance of 10 km the propagation is consistent with a 6 dB decrease in SPL per doubling of distance.

The right-hand panel, Fig. 3(b), repeats the calculation of relative levels using ISO 9613-2 (1996).[1] Smoothing was not required for this data. Note that these calculations are for a height of 4 m, where ISO 9613-2 (1996) indicates there is more ground attenuation at 125 Hz than at 500 Hz. Below 0.5 km Figs. 3(a) and 3(b) suggest geometric spreading is comparable to a 6 dB decrease in SPL per doubling of distance and the main difference between panels is an approximate 3 dB reduction in SPL in the ISO 9613-2 (1996) calculations. The figure shows only the FFP results for the most favorable downwind propagation direction so this difference is to be expected as the ISO calculations give the same results both upwind and downwind. In the ISO calculations an underestimate of downwind levels is compensated by an overestimate in upwind SPL, Arguably, the results in Fig. 3 show consistency between ISO and FFP results for distances less than 1 km, which is the range over which the ISO standard was intended to be used (ISO 9613-2, 1996). Large differences between FFP and extended ISO 9613-2 (1996) calculations are only apparent at 1.7 km or more.

For comparison to Fig. 3, Fig. 4 shows similar smoothed data at 4.8 Hz for generic Harmonoise weather classes. Similar to Fig. 3, at distances less than 1 km, the relative difference from a 6 dB decrease in SPL per doubling of distance, and +6 dB ground reflection is near zero. Table II shows numerical results for the same data at 10 km, and shows that for 8 of the 25 Harmonoise weather classes the deviation from the reference condition exceeds 8 dB (refer to Table I for class descriptions). Similar patterns were found at 1.6 Hz for all classes (data not shown). At 20 and 70 Hz, for the W4 and W5 wind speed classes, only W4S5 had TL more favorable than a 6 dB decrease in SPL per doubling of distance, but the patterns for W1 and W3 classes were similar to Table II.

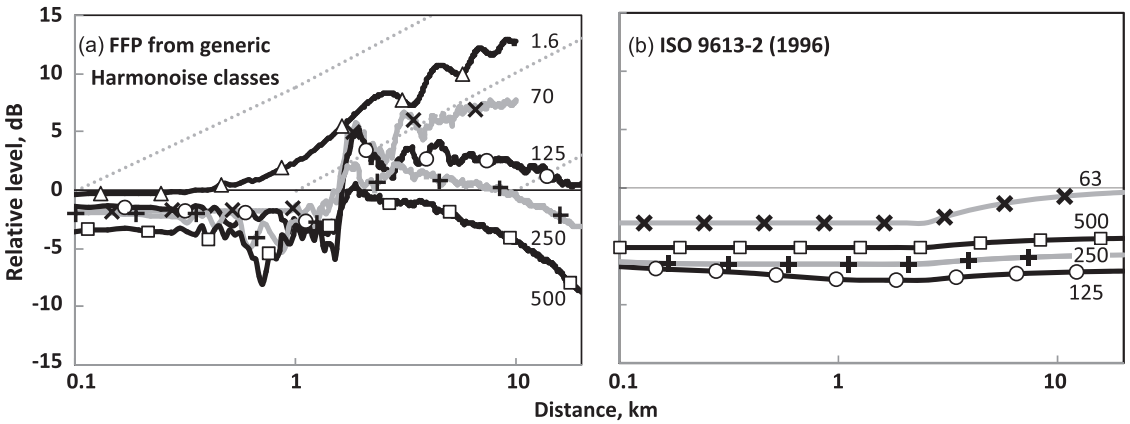

FIG. 3. Relative level directly downwind of a point source at 80 m height with reference to a coherent +6 dB ground reflection and a 6 dB decrease in SPL per doubling of distance. (a) Smoothed FFP calculations for meteorological class W1S5 in a downwind direction; (b) same calculations repeated using ISO 9613-2 (1996), which are not a function of wind direction. Frequencies used in calculations in (a) include △, 1.6 Hz; and ×, 70 Hz, ○, 125 Hz; +, 250 Hz; □, 500 Hz; (b) is similar except the lowest frequency is ×, 63 Hz. The angled dotted lines have a slope of 3 dB per doubling of distance. Higher relative levels in the figures are associated with higher SPL at dwellings.

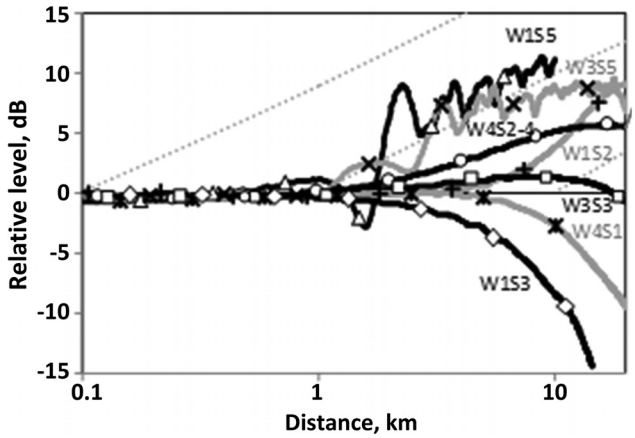

FIG. 4. Smoothed FFP data for a frequency of 4.8 Hz showing relative levels downwind for a single point source at 80 m height with reference to a 6 dB decrease in SPL per doubling of distance and coherent +6 dB ground reflection. From the uppermost to the lowermost curve, the classes represented include: △, W1S5; ×, W3S5; ○, W4S2 (similar to W4S3 and W4S4); +, W1S2 (similar to W2S1); □, W3S3; ж, W4S1; ◇, W1S3. The data are for the direct downwind direction, i.e., the most favorable propagation direction. The relative levels shown in this figure at 10 km are summarized in Table II for all 25 Harmonoise classes.

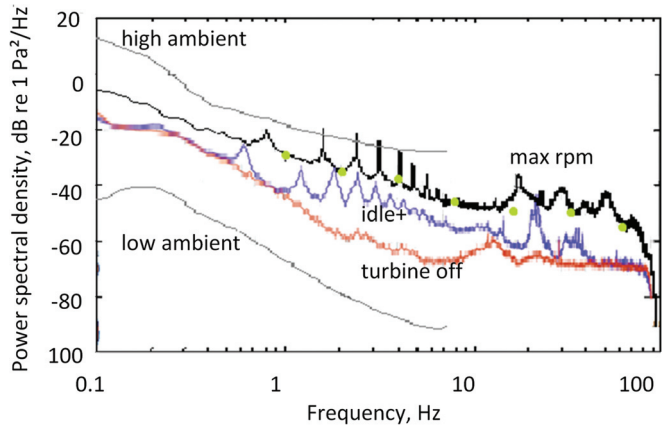

FIG. 5. SPL measurements of power spectral density made 125 m from the base of a wind turbine: Black curve (labeled max rpm), turbine operation at maximum rpm (0.8 Hz fundamental, Edwards, 2015); blue curve (labeled idle+), turbines operation slightly above idle speed (0.6 Hz fundamental); red curve (labeled turbine off), same conditions as blue curve, with turbines off. For reference, the ambient noise from Bowman *et al.* (2005) high ambient noise model (95th percentile) is shown in the uppermost curve; and the low ambient noise model (5th percentile) is shown in the lowermost curve.

IV. FIELD MEASUREMENT VALIDATION OF FFP CALCULATIONS

A. Identification of wind turbine noise

Figure 5 shows three measurements acquired 125 m from the wind turbine base measured using the microbarometer with soaker hose windscreen. The lowest red curve shows the ambient noise under a 15 min scheduled shutdown period when the wind speeds were about 4 m/s. The next highest blue curve shows the same conditions with the wind turbine operating at just above idle speed (0.5 Hz) at a fundamental frequency of 0.6 Hz. A comparison of levels with the wind turbine ON and OFF shows that wind turbine harmonics are readily visible from 0.6 to 6 Hz, with some broad peaks at higher frequencies. The next higher black curve in Fig. 5 is the wind turbine spectrum with the turbine operating at full speed (i.e., 16 rpm, which occurs for wind speeds at or above 8 m/s). At this speed the fundamental is at 0.8 Hz and a number of harmonics are visible, including some broad peaks at 20, 45, and 70 Hz. The harmonics and broadband spectral peaks seen in the upper curve were used when modeling the wind turbine noise propagation.

TABLE II. Generic FFP calculations for all Harmonoise weather classes at a frequency of 4.8 Hz approximately 10 km downwind of the source showing decibel levels relative to a single point source at 80 m height with reference to a 6 dB decrease in SPL per doubling of distance and coherent +6 dB ground reflection.

	S1	S2	S3	S4	S5
W1	9[a]	4[a]	−7[a]	8[a]	11[a]
W2	4[a]	−5	−3	9	9
W3	−4	−3	1	9	9
W4	−2	5	5	5	9
W5	6	6	6	6	6

[a]Indicates approximately omnidirectional propagation.

In Fig. 6, harmonics associated with operation of the wind turbines are clearly identifiable at distances up to 10 km away. Near the wind turbine the noise is comprised of several harmonics of the fundamental blade passage frequency which are observed near 0.513 Hz for wind speeds less than 8 m/s, and transition to 0.806 Hz at higher wind speeds. These frequencies correspond to the nominal rotor rotation speeds of 10 to 16 rpm.

In Fig. 6, at 2.5 km and beyond, wind turbine SPLs would be expected to drop by more than 20 dB compared to the levels at 125 m. This makes the wind turbine harmonics more difficult to identify. At and beyond 2.5 km only the 16 rpm harmonics are visible, due to the higher sound power levels associated with this rpm. Particularly at night, the wind speed at hub height can be more than double the measured 10 m wind speeds shown in Fig. 6.

In Fig. 6, the upper 20 m/s wind speed curves show large contributions from wind noise at the 2.5 km station. At this location, at frequencies between 1 and 2 Hz the wind noise levels appear to be almost 15 dB higher than the levels at the 5 km station. The 2.5 km station was situated in an open field with a few trees, while the 5 km station was immediately adjacent to a long copse of trees to the north and a larger wooded area to the southwest.

One factor that affects the ability to measure and identify wind turbine spectral peaks is the ambient noise. Both Figs. 5 and 6 show the high and low noise models of Bowman *et al.* (2005), which characterize infrasound from 21 globally distributed, state of the art, infrasound arrays that are comparable to those in the current study (Sec. II F). At 125 m the high noise model by Bowman *et al.* (2005) passes through the peaks of the wind turbine noise. In the 4 Hz octave band, the high noise model (95th percentile) and wind turbine noise are both approximately 70 dB. This suggests that at the base of the wind turbines to have a 95% confidence of that wind turbine noise would be dominant,

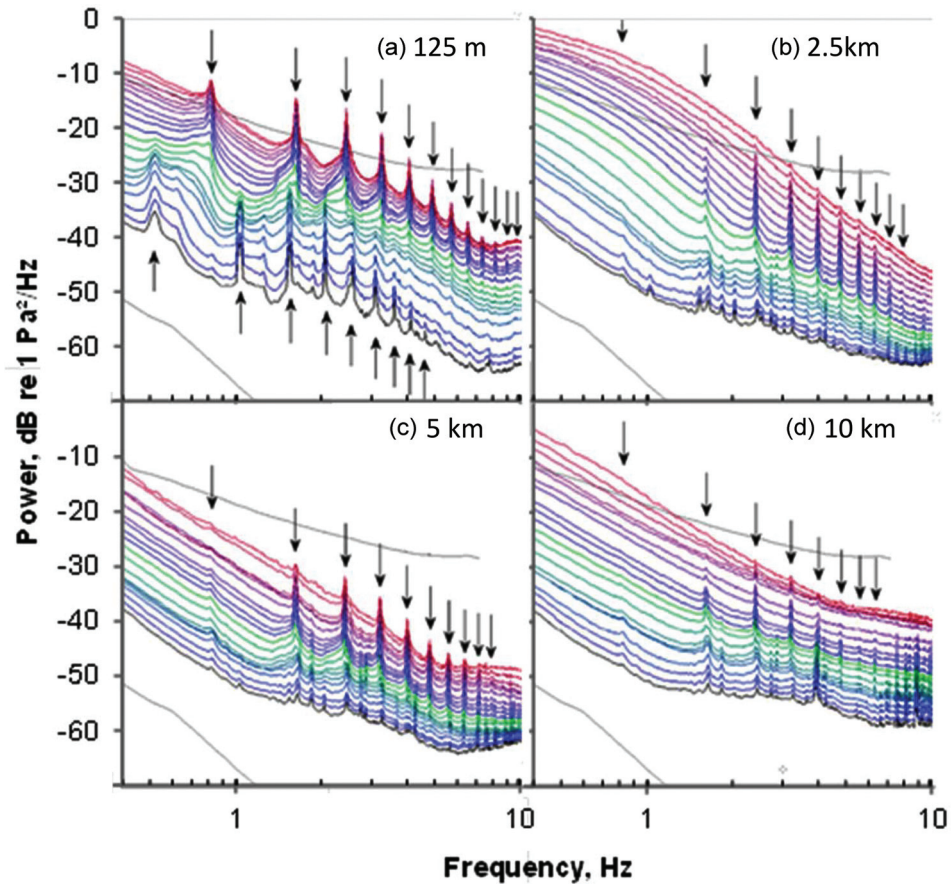

FIG. 6. Adapted from Edwards (2015) inter-quartile means for measured 10 m height wind speeds in 1 m/s intervals from 1 m/s (bottom curve in group) to 20 m/s (top curve in group) at a distance from turbine of (a) 125 m, (b) 2.5 km, (c) 5 km, and (d) 10 km. The uppermost curve is the high global noise limit measured at infrasound monitoring stations (Bowman *et al.*, 2005) and the lowermost curve is the corresponding low global noise measurement. Arrows above each set of curves show 0.8 Hz fundamental and associated harmonics, and in (a) the arrows below the set of curves show 0.5 Hz fundamental and its harmonics.

narrowband filters would be required, and octave band filters would not be sufficient. Conversely, the low noise model in the figure is 4 to 6 orders of magnitude lower than the high noise model, which suggests that under some conditions it may be possible to measure wind turbine noise at large distances. This is consistent with the results of Marcillo *et al.* (2015), who measured wind turbine noise at a distance of 90 km.

Figure 7 shows spectra identified under well-defined meteorological conditions. The measured wind speed is 5.0 m/s at 10 m height. In contrast to Fig. 6, where spectral contributions from many meteorological conditions are averaged, in Fig. 7 a number of harmonics stand out clearly from the background noise.

The fundamental blade passage frequency was difficult to observe at distances larger than 125 m. PE calculations at 0.5 Hz indicated propagation at this frequency was never better than a 6 dB decrease in SPL per doubling of distance out to a distance of 10 km.

B. Extrapolation of weather data

Figure 8 shows data from the on-site weather station (Sec. II F) extrapolated to 1 km height using similarity theory on an occasion when spectral peaks were readily identified. The middle plot is the downwind wind speed, and the right-hand plot is the effective sound speed in the direction of the dwelling, which takes into account the wind direction.

Similarity theory was not developed for high altitudes, and as a result the calculated profiles have an approximately constant linear slope above 50 m. As seen in Fig. 8 this can result in unrealistic profiles at higher altitudes. Despite this

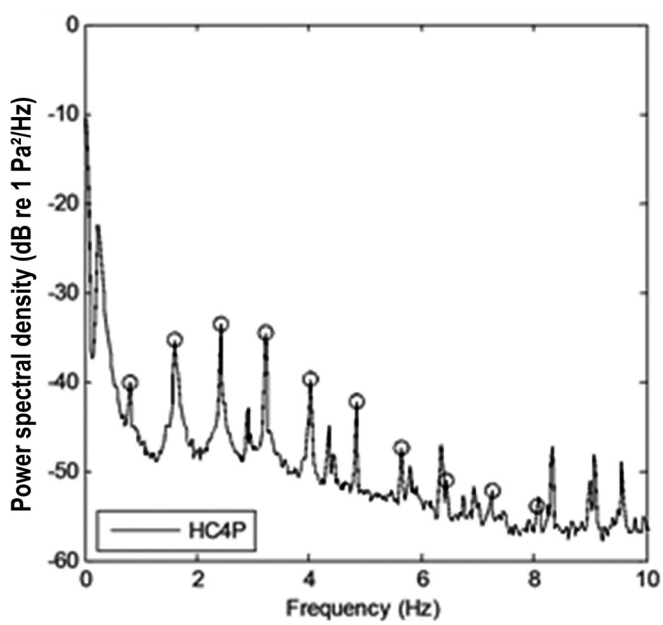

FIG. 7. Averaged wind turbine spectrum at 10 km for a single weather condition (wind speed 5 m/s @ 10 m height, 1.35 °C temperature difference, and 40° off downwind (from Daigle and Stinson, 2014).

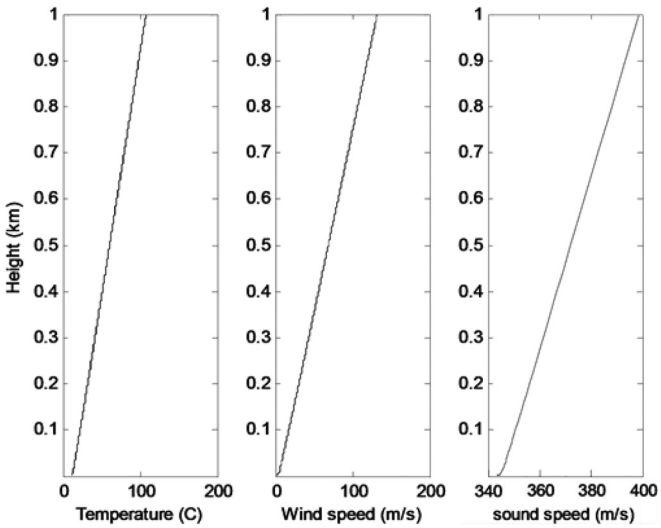

FIG. 8. Data from the on-site weather station extrapolated using similarity theory to 1 km height early on a summer morning with a strong inversion [wind speed 5 m/s @ 10 m height, 1.4 °C temperature difference (between 2 and 10 m height), 40° off of downwind]. Left panel: Calculated temperature, middle panel: downwind wind speed, and right panel: effective sound speed in the direction of the dwelling. Note that the profiles become unrealistic at higher altitudes (from Daigle and Stinson, 2014).

limitation, the profiles in Fig. 8 were still usable; due to the high density of sound rays near the ground, the SPLs were found to be controlled by the sound speed profile below about 200 m. This was confirmed by systematically removing the higher altitude rays until the levels at the larger distances begin to change (i.e., drop). The rays above 200 m were found to be insufficient to alter the levels at all distances out to and including at 10 km.

Due to the 5 m/s wind speed measured at 10 m height, the data in Fig. 8 are clearly associated with Harmonoise wind speed class W3, but observations of cloud cover were not available to determine the stability class. The strong temperature inversion measured near the ground suggests this is a clear night so that the appropriate Harmonoise class would be W3S5. In reality the sound speed gradient in Fig. 8 is stronger than that found in any of the Harmonoise weather classes. This shows that Harmonoise weather classes are not always a good substitute for measured data.

C. Observations associated with class W3S5

Considering only those classes where the wind speed ensures the wind turbines are reliably operational (i.e., W3, W4, and W5), FFP calculations show the propagation conditions most conducive for long distance identification of wind turbine noise occurs for clear nights with relatively low wind speeds, i.e., meteorological class W3S5 (see Fig. 4). This class occurs on average 1.8(5) h in each 24-h period (Fig. 1). The ability to measure wind turbine noise would be expected to be maximal in W3S5 for a number of reasons: (1) at the wind turbine hub height this class includes the wind speed where the turbines produce near maximum sound power; (2) W3S5 has one of the most favorable TL (Table II, Fig. 4); (3) W3S5 has the highest wind shear (after W2S5) so that wind noise and background ambient ground level noise due to wind interacting with vegetation are low; and (4) W3S5 occurs at night when the anthropogenic background ambient noise is lowest.

Analysis of microbarometer SPL showed wind turbine spectral peaks were identified on 13 nights corresponding to strong inversion conditions (i.e., clear night) and wind speeds of about 5 m/s (measured on-site at 10 m height). The corresponding profiles are seen in Fig. 8. This corresponds to the W3S5 meteorological class, and based on Fig. 1 this class would be expected for approximately 360 h in the 200 nights in which the data were analyzed. The amount of data collected are consistent with the expected frequency of occurrence of this class because the analysis time in a given night was 1 h, and during this time the results had to be stable and free of excessive background noises.

Samples of data with identifiable spectral peaks (harmonics) measured on 10 nights in the summertime (typically in the early morning) during a downwind inversion condition are shown in Figs. 9(a)–9(c). Below 5 Hz the data are in good agreement with predictions. Between 5 and 20 Hz background ambient noise appears to be influencing the results at 10 km, and all distances seem to be affected by background ambient noise at 70 Hz. The FFP calculations based on onsite meteorology are closer to the measured SPL than those using the generic Harmonoise classes. Differences between the two calculation methods on the order of 5 dB are common.

Despite averaging over 1 h, the results vary in a range of up to 6 dB. This range is likely influenced by varying meteorological conditions along the propagation path, as well as the fluctuations seen in Fig. 2.

D. Seasonal changes in propagation

Snow cover can produce large changes in SPL near 300 Hz (Daigle and Stinson, 2005, Internoise). However, in the present study, measured over 13 consecutive months, for frequencies at and below 70 Hz, no systematic seasonal differences in SPL were found. In the W3S5 meteorological class in Fig. 9 measurements were observed in the months of June when crops were growing; in November after harvest; and in January when the study area had an accumulation of 1 m of snow.

E. Daytime

Based on measurements by Willshire and Zorumski (1987) it could be expected that the wind turbine signature would be frequently measurable during high W5 winds in the daytime (see also Table II). This was not the case in the Health Canada study area, in part because the W5 classes are not common (Fig. 1), and the Willshire and Zorumski (1987) measurements were facilitated by higher source power levels than found in the Health Canada study. Measurements were, however, identified for W4 wind speeds which compared to W5 classes, have similar TL and lower ground level wind speeds.

Wind turbine noise was also measured downwind at 3.2 Hz (Fig. 10) at 2.5 and 5 km distance. Due to the

measured lapse, this suggests clear skies and W4S1 conditions. Both calculation methods underestimated the measured results by at least 5 dB. At other frequencies, e.g., 5.6 Hz in Fig. 10, the calculated levels were lower and no spectral peaks were observed. At 10 km the figures show generic calculations are almost 10 dB different from calculations using actual meteorological conditions.

Wind turbine noise was measured upwind of the turbines during a weak daytime inversion under W4 wind speeds in Fig. 11. Harmonics at 2.4, 3.2, 4.0, and 4.8 Hz were found at 125, 2.5, and 5 km from the turbines (Daigle and Stinson, 2014). This result closely matched the PE calculations based on onsite meteorology. Because of the daytime inversion, this condition is not part of the Harmonoise weather classes, and available generic calculations for the closest daytime W4 classes tended to underestimate the PE calculations.

F. Comparison of generic meteorological classes and on-site meteorology

As indicated above, sound speed profiles based on measured onsite meteorology can represent conditions that are not included in the Harmonoise weather classes. Figure 12 shows predicted SPL levels where onsite measurements had a weak temperature inversion, while the generic Harmonoise temperature profile was associated with a lapse. In this case calculations using the generic Harmonoise classes, although similar at a few hundred meters, differ by over 20 dB at 10 km distance. When studying specific weather conditions, particularly at large distances, the use of the generic Harmonoise classes could result in significant errors and would only be recommended when no other information is available.

V. COMPARISON OF CALCULATION METHODS AT DWELLINGS

A. Field measurement of wind turbine sound power levels

Figure 13 shows average octave band wind turbine spectra as a function of wind speed averaged over 9 of the wind turbine models (with 1.5 and 3 MW electrical power output and omitting the lowest power 660 kW model due to its reduced electrical power and size). In this figure octave band data are used to allow comparison to manufacturer's specifications and to allow comparison of different wind turbines which may have different rotational speeds or different bandwidths for tones in their harmonics. When A-weighted, the results for a nominal 8 m/s wind speed at 10 m height (per IEC 61400-11, 2012) were on average 104.2(2.0) dBA, approximately equal to the average of the manufacturers specifications. At 8 m/s the unweighted sound power levels were 125.5(3.0) dB (where the sound power level for individual turbines ranged from 120 to 130 dB), and were typically 21(4) dB higher than the A-weighted sound power levels.

Below 4 Hz the standard deviation increases and spectral shapes are less similar as a function of wind speed. A large component of these differences is differing wind turbine rpm which changes the distribution of harmonics in the lowest frequency bands. Data are also less reliable in this range due to adjustment to compensate for low frequency cutoff of the microphones.

The wind turbine noise spectra shape shows little change as a function of wind speed. As the wind speed dropped from 8 m/s wind speed to 3 m/s the standard deviation increased to approximately 5 dB. This larger standard deviation is a result of increasing variation in turbine

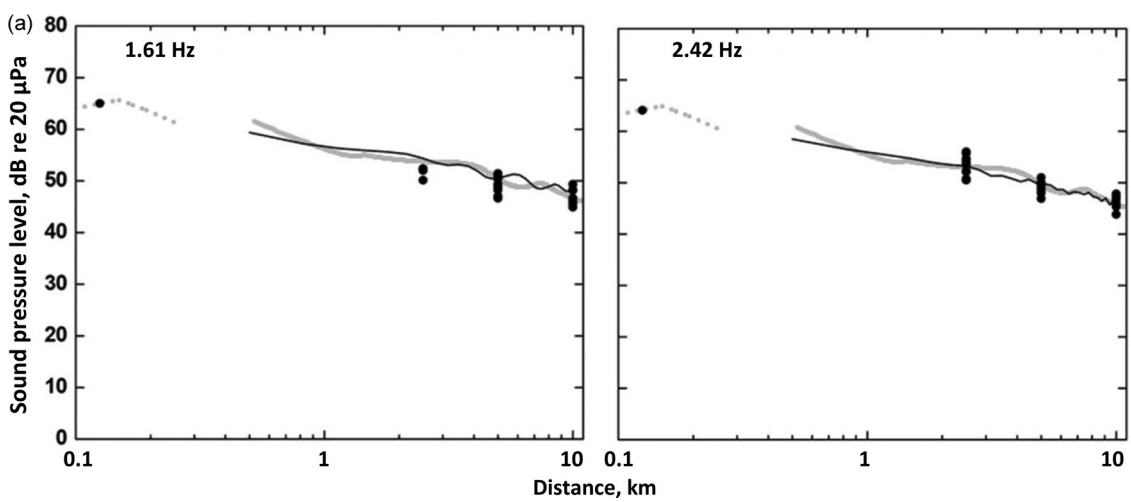

FIG. 9. (a) Comparison between predicted and measured levels for strong inversion conditions during early morning in the summertime. Filled circles are onsite measured SPL data from ten nights. The thin black lines show the smoothed FFP calculated SPL for onsite conditions (wind speed 5 m/s @ 10 m height, 1.4 °C temperature change from 2 to 10 m height, 40° off from downwind) using similarity theory (from Daigle and Stinson, 2014). In all panels the thick gray lines are generic calculations for Harmonoise class W3S5 (40° off from downwind). The measurement at 125 m is influenced primarily by the single nearest wind turbine while the other measurements are equally influenced by 4 wind turbines. (a) Measured SPL and FFP calculations at 1.61 and 2.42 Hz compared to generic Harmonoise calculations at 1.6 Hz; (b) measured SPL and FFP calculations at 3.22, 4.03, 4.83, and 5.64 Hz compared to generic Harmonoise calculations at 4.8 Hz; (c) in the top panel, measured SPL and FFP calculations at 20 Hz are compared to generic Harmonoise calculations at 20 Hz, and in the bottom panels the generic Harmonoise calculations are made at a frequency of 70 Hz.

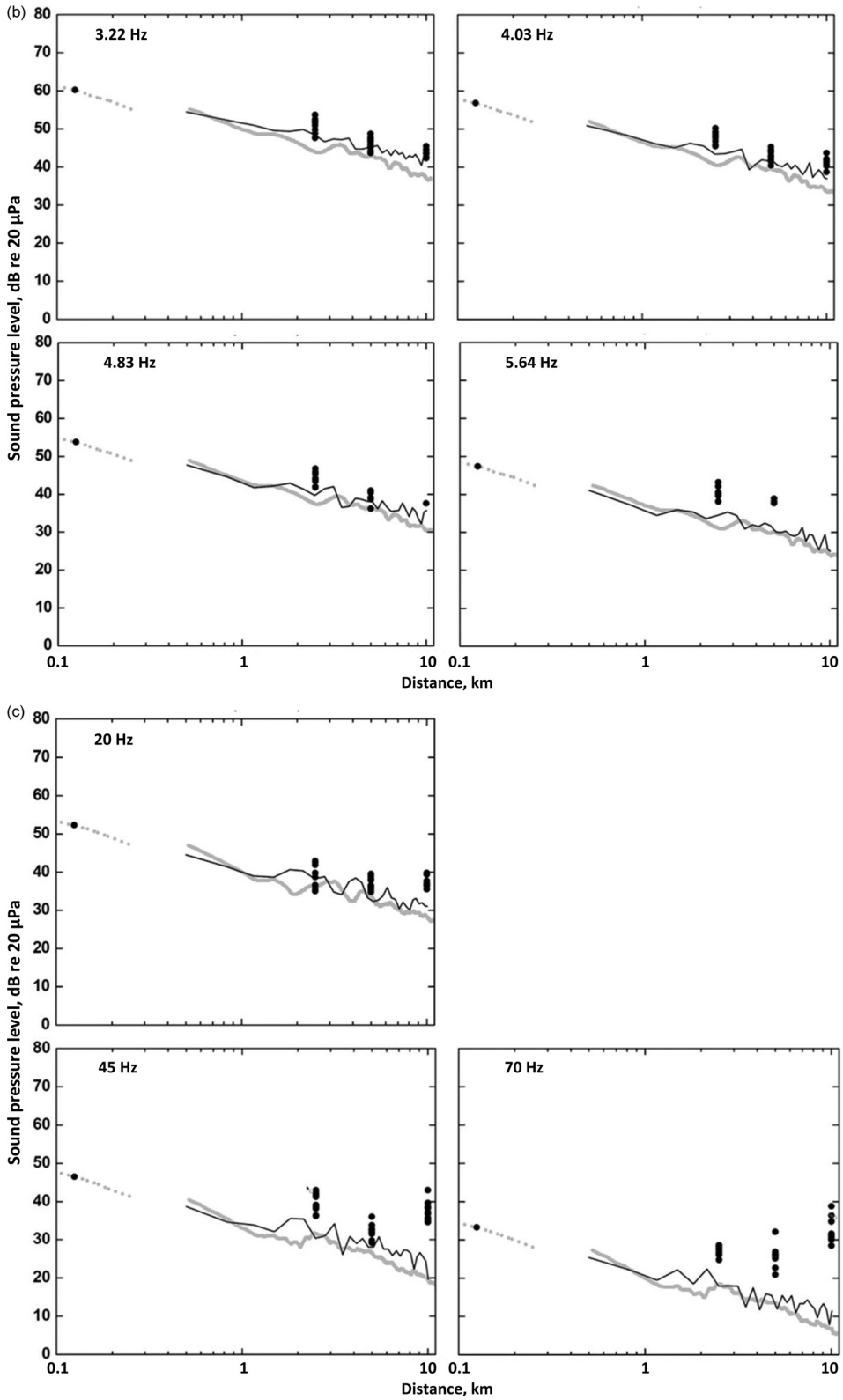

FIG. 9. (*Continued*)

operating conditions, i.e., some idling at 3 m/s, some above cut-in, as well as to changes in rpm.

Near the base of the wind turbines, comparison of the two wind screening methods suggests that between 0.8 and 20 Hz the soaker hose provides approximately 20 dB more attenuation of wind noise than the IEC primary and secondary hemispherical windscreens. Because the IEC measurements were 1/3 octave band, and had a less effective

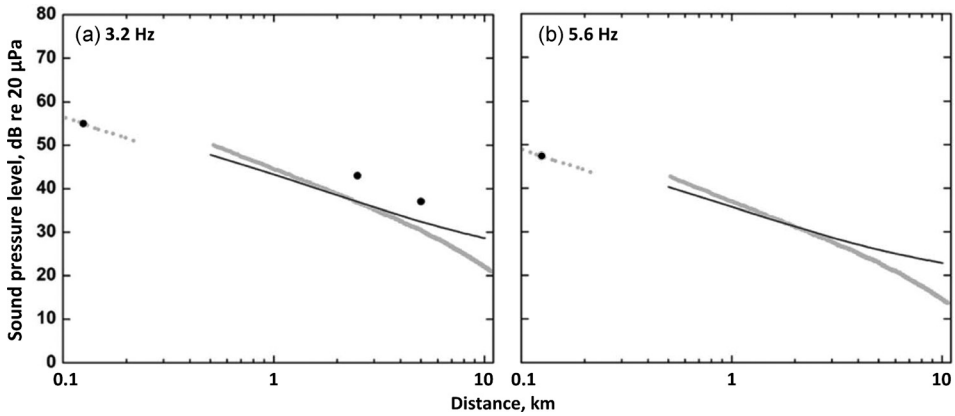

FIG. 10. Comparison between predicted and measured levels at 3.2 and 5.6 Hz for weak inversion conditions during the afternoon in the summertime. Circles are onsite measured data (note that there were no identifiable harmonics beyond 125 m at 5.6 Hz). The thin black lines show the smoothed FFP calculated levels for onsite conditions (8.4 m/s at 10 m height, −0.5° temperature lapse measured between 2 and 10 m height, 15° off downwind) using similarity theory (from Daigle and Stinson, 2014), and the thick gray lines are generic calculations for class W4S1 at 4.8 Hz (15° off downwind).

windscreen, IEC measurements of wind turbine noise were effectively obscured by microphone wind noise for wind speeds above 8 m/s (measured at 10 m height).

B. Calculated SPL at dwellings

At each dwelling the SPL due to wind turbines was calculated using the sound power level for each wind turbine model (similar to Fig. 13) and the generic TL based on Harmonoise weather classes (e.g., Figs. 3 and 4). As an example, using the 31.5 Hz octave band the average sound power level is 111.3 dB. Assuming a 6 dB decrease in SPL per doubling of distance and a +6 dB ground reflection (Fig. 3), the corresponding SPL at a 125 m distance becomes 61.6 dB. This level approximates the average

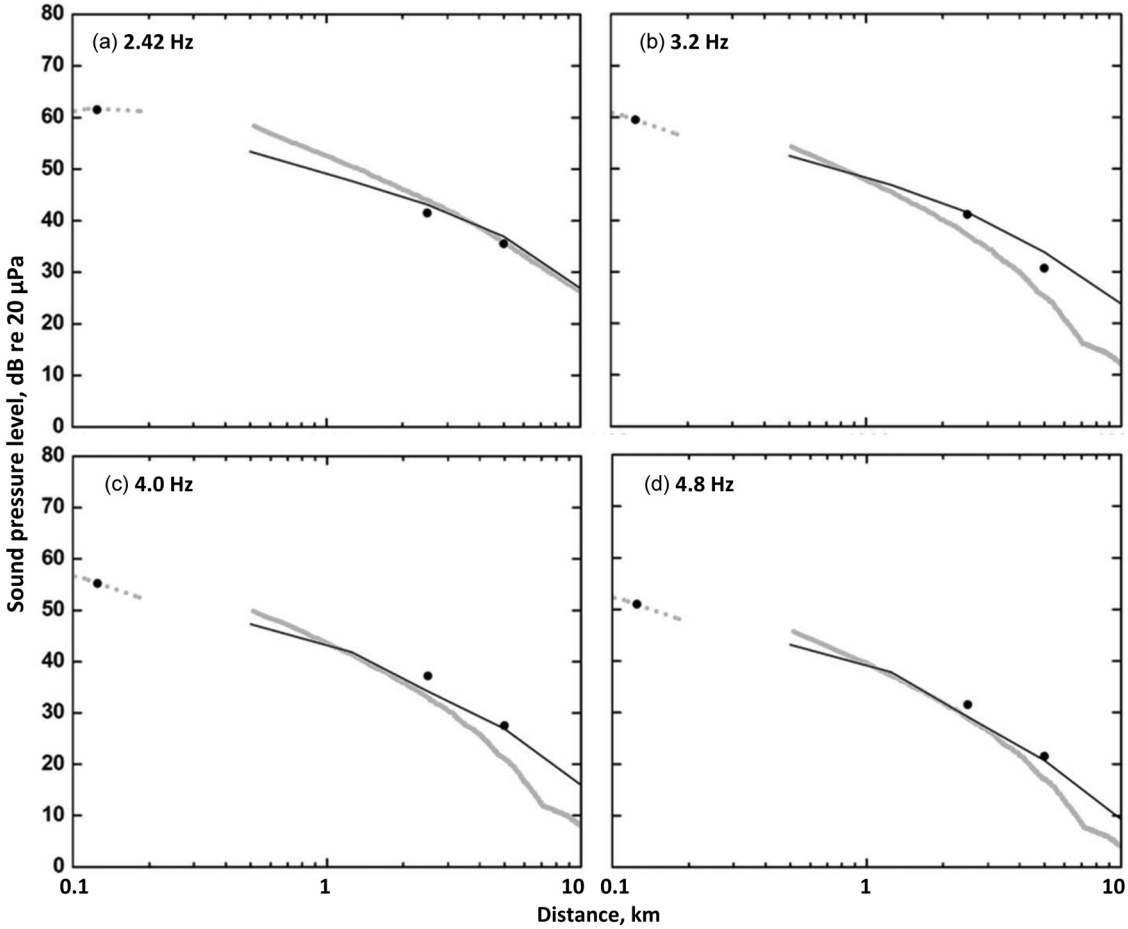

FIG. 11. Comparison between predicted and measured levels for weak inversion conditions during early afternoon in the summertime. Filled circles are onsite measured SPL. The thin black lines show the smoothed PE calculated levels for onsite conditions (7 m/s @ 10 m height, 0.5° temperature inversion measured between 2 and 10 m height, 125° off from downwind) using similarity theory (from Daigle and Stinson, 2014). The thick gray lines are generic calculations for class W4S3 at 125° off downwind.

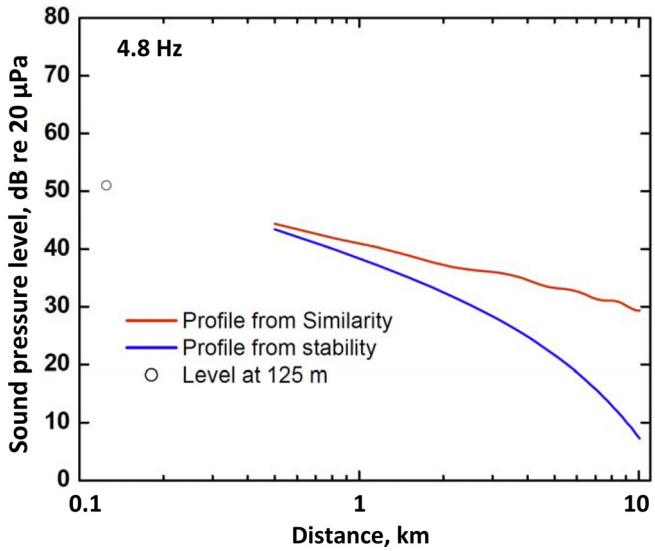

FIG. 12. (Color online) Comparison of predicted SPL at 4.8 Hz using weather conditions measured onsite (upper curve for 2.0 m/s @ 10 m height, 0.3° temperature inversion measured between 2 and 10 m height, 35° off from downwind) and corresponding calculation based on reported wind speed and cloud cover from a nearby weather station (lower curve, generic Harmonoise class W2S1 at 5° off from downwind) from Daigle and Stinson (2014). Although data were obtained for the same time period the onsite weather station and historical weather data (Environment Canada, 2016) had wind direction differing by 40°.

hearing threshold of 59.5 dB (ISO 226, 2003). The slope of the hearing threshold is 26 dB per octave, and this is many times greater than the slope of the wind turbine spectra (Fig. 13). This suggests that at frequencies below 31.5 Hz the noise from a single wind turbine would tend to be below the hearing threshold. At a distance of 10 km downwind, for common favorable propagation conditions at night, W3S5 (Table II, Fig. 1) the level from a single wind turbine would be 33 dB based on generic FFP calculations. At this distance and frequency, hundreds of wind turbines would be required to bring the noise to the average threshold of hearing.

For the overall G-weighted levels, the average sound power is 121.1 dBG, and at 125 m distance the level is 72.7 dBG. Near the base of the wind turbine this level is over 12 dB below the 85–90 dBG threshold typical for human perception (Broner, 2010; ISO 7196, 1995). The G-weighted levels are based on the infrasound perception threshold between 1 and 16 Hz, so that a very large number of turbines would be necessary before infrasound levels become relevant to wind turbine noise.

To obtain realistic estimates of wind turbine perceptibility, data from the 399 wind turbines in the Health Canada study can be used. Figure 14 shows the SPL for dwellings calculated for different frequency weightings using the generic Harmonoise classes for FFP calculations. Most environmental assessments currently use A-weighted values, so these A-weighted values are used as a reference for comparison. Compared to the generic FFP calculations the A-weighted data have a larger range because atmospheric absorption and ground absorption cause significant reductions in A-weighted levels at large distances, but has little effect on frequencies below 63 Hz.

Statistically there was little difference between calculated results in different frequency ranges. Figure 14 shows that compared to A-weighted values, the unweighted FFP

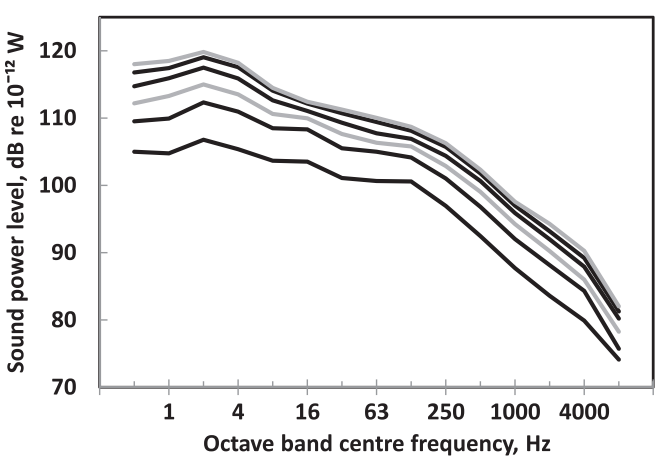

FIG. 13. Average sound power levels from 9 of the 10 wind turbine models (electrical power 1.5 to 3 MW, one turbine with 0.66 kW electrical power was removed from average) as a function of hub height wind speed extrapolated to 10 m height (per IEC 61400-11, 2012). The lowest line is for 3 m/s wind speed; the next highest lines increase consecutively in 1 m/s increments to the highest curve at 8 m/s wind speed. The 5 and 8 m/s wind speed results are shown by gray lines.

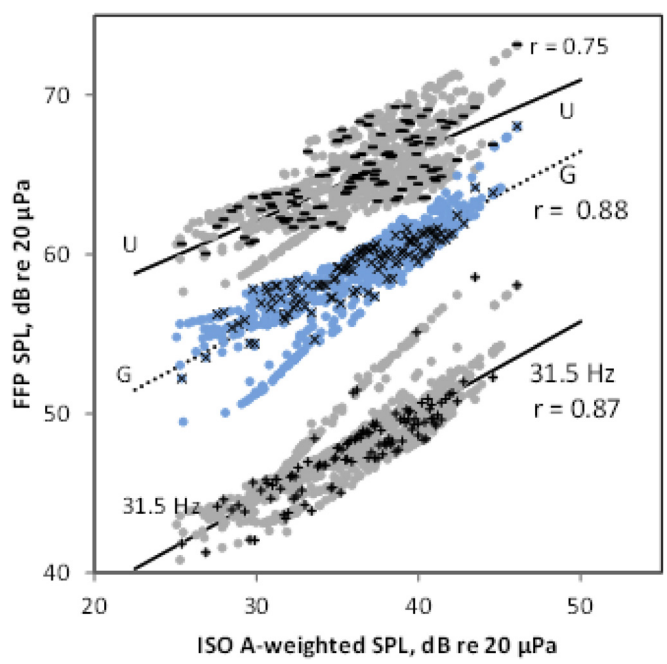

FIG. 14. (Color online) Comparison of calculated SPL at dwellings for 8 m/s wind speed using generic Harmonoise FFP calculations with respect to A-weighted calculations (nominal bandwidth 63 Hz to 3 kHz) using ISO 9613-2 (1996). This plot shows that the infrasound metrics may not be well predicted if only A-weighted values are available. All results are based on a yearly average estimate including wind speed, TL, and atmospheric absorption. In addition the generic FFP data also account for wind direction and weather class. Every tenth result is indicated by a symbol: +, 31.5 Hz SPL; ×, G weighted (G) SPL; −, unweighted (U) SPL (nominal bandwidth 0.5 to 125 Hz). The lines show the best linear fit through the associated data. The Pearson correlation coefficient between the two calculation methods is shown near each line.

yearly average estimates had a Pearson's r greater than 0.75. Similar results were found for the 16, 31.5, and 63 Hz octave bands where r was at least 0.87. The high correlations suggest that the data from the Health Canada study would not allow an evaluation to determine which frequency(s) are most relevant to a specific effect of wind turbine noise.

Figure 14 can be used to evaluate the perceptibility of the infrasound noise. The G-weighted levels do not appear to be relevant as they are below 68.0 dBG, more than 12 dB below the 85 to 90 dBG threshold typical for human perception (Broner, 2010; ISO 7196, 1995). Unweighted levels of 120 to 128 dB are used as limits for blast noise (e.g., ONMOE, 1978), and all levels in Fig. 14 are below 73.2 dB, far below these criteria.

Figure 15 shows a comparison of SPL calculated using FFP based on Harmonoise and extended ISO calculations for the same dwellings used in Fig. 14. There is a strong correlation between the two methods ($r \geq 0.90$), the slope is close to 1, and the scatter in the points is small compared to the expected 3 dB standard deviation in the ISO calculations. The agreement is better for the lowest SPLs, i.e., for longer distances.

ISO 9613-2 (1996) includes a meteorological correction for wind direction. For SPLs above the median in Fig. 15, the ISO 9613-2 (1996) correction would be near 0 and for the lowest levels in Fig. 15 the correction would approach 2 dB (to be subtracted from the levels). For the data in Fig. 15 this would improve the agreement at 31.5 Hz, and worsen the agreement in the unweighted levels. It should be noted that ISO 9613-2 (1996) was not intended for use at frequencies below 63 Hz.

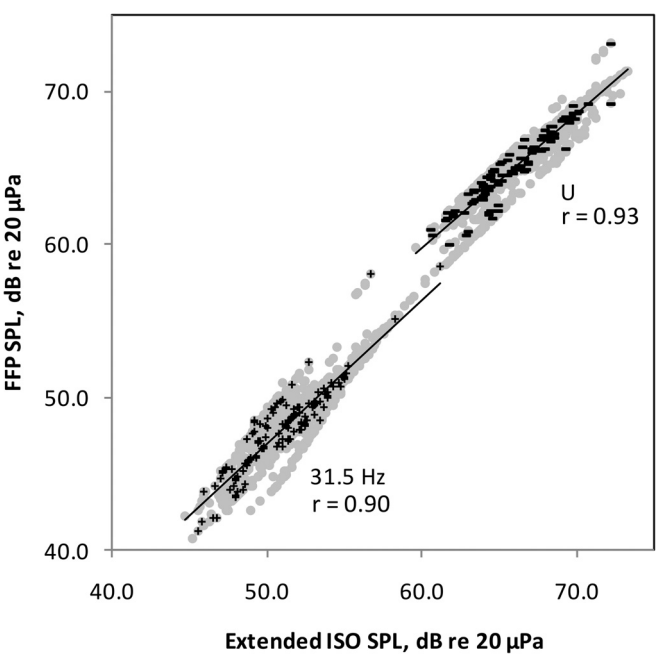

FIG. 15. Comparison of calculated SPL at dwellings for 8 m/s wind speed using FFP with respect to extended low frequency calculated SPL using ISO 9613-2 (1996). All results are based on a yearly average estimate including wind speed, TL, and atmospheric absorption. The FFP data also accounts for wind direction and weather class. Every tenth result is indicated by a symbol: +, 31.5 Hz SPL; −, unweighted (U) SPL (nominal bandwidth 0.5 to 125 Hz). The lines show the best linear fit through the associated data. The Pearson correlation coefficient between the two calculation methods is shown near each line.

The ANSI S12.2 (2008) criterion for moderately noticeable rattles is 65 dB in the 31.5 Hz octave band. This level is not exceeded in Fig. 14 where the highest calculated level was 58.6 dB at 31.5 Hz. The results are similar at neighboring octave bands; at 16 Hz 59.7 dB was the highest calculated level and 54.1 dB was the highest calculated level at 63 Hz. Both of these neighboring levels are also below the ANSI S12.2 (2008) criteria. In the Health Canada survey, of the 1238 subjects (in 1238 dwellings), 58 subjects noticed vibrations and 19 were highly annoyed by the vibrations. Rattle sounds can cause a large increase in annoyance (ANSI S12.9 Part 4, 2005) so the relatively small number of persons who noticed or were highly annoyed by vibrations in the Health Canada study is perhaps to be expected. The survey respondents who noticed vibrations tended to be at the higher calculated SPL and within 15 dB of the ANSI S12.2 (2008) criteria.

VI. SUMMARY AND CONCLUSIONS

Predictions verified by measurements show that under common meteorological conditions wind turbine noise can be measurable at 10 km downwind of wind turbines. Under these conditions, the downwind infrasound propagation (including air and ground absorption) is more favorable than a 6 dB decrease in SPL per doubling of distance, i.e., in class W3S5 which is estimated to occur on average 1.8(0.5) h a night in the area of the Health Canada study. Favorable propagation conditions could also occur throughout the night and during high winds in the daytime; however, under these conditions, measurement of wind turbine noise is made difficult by wind noise on the microphone and the noise from the wind interacting with vegetation.

The ability to measure wind turbine infrasound was influenced by ambient infrasound, the effectiveness of the windscreens, and the presence of shielding vegetation. Wind turbine SPLs are low enough that effective windscreens and narrowband analysis are required to ensure a 95% confidence of being able to distinguish wind turbine noise from ambient infrasound, even at the base of the wind turbines. For example, following the IEC 61400-11 (2012) wind turbine sound power standard, in 1/3 octave bands, using the specified windscreens near the base of the wind turbines it became difficult or impossible to measure wind turbine infrasound at wind speeds above 8 m/s. Conversely, background ambient infrasound pressure levels can also be significantly lower than wind turbine SPLs. Wind turbine noise was measured at a 10 km distance in the current study.

In the Health Canada study it was not possible to conclusively determine the frequencies having the largest effect on survey respondents. The shape of the spectra from the 9 wind turbines in the study were very similar, not strongly affected by wind speed, and the standard deviation in octave bands was 2 to 3 dB for frequencies between 4 and 2000 Hz. As a result, at the dwellings in the Health Canada study, individual frequency bands, or frequency weightings, are all

correlated, i.e., Pearson's r was 0.75 to 0.93 for all comparisons of long term average data. In the Health Canada study, the infrasound levels were compressed into a smaller decibel range than found for the A-weighted SPL, so to effectively evaluate infrasound data high accuracy may be required. In the Health Canada study, improvements in accuracy required to evaluate infrasound would not likely be justified. Infrasound levels were found to be more than 17 dB below perceptible levels at all dwellings.

To determine if infrasound is close to perceptible levels it appears that ISO calculations can be extended to approximate the long term average infrasound SPL, provided that the most affected residences are within a few kilometers of the nearest wind turbines. If infrasound approaches perceptible levels, for calculations over long distances, or for specific meteorological classes, the improved accuracy of the FFP calculations using measured atmospheric properties as a function of height would be recommended.

ACKNOWLEDGMENTS

The authors acknowledge Wayne Edwards for his significant contributions to this work in its design, implementation, and interpretation of results. The authors also acknowledge Eric Lemay for his assistance in data collection. The authors appreciate the cooperation received from wind turbine manufacturers, operators, and landowners toward the completion of this study. The authors have declared that no competing interests exist.

[1]At 63 Hz, in ISO 9613-2 (1996) the ground reflection increases SPL by 3 dB near the source and the effect of the ground reflection monotonically increases to 6 dB at an infinite distance. For an 80 m height source, in the short distance range of 2.4 to 3.3 km, the ISO 9613-2 (1996) propagation appears to be more cylindrical than spherical.

ANSI (**2005**). S12.9 Part 4. *Quantities and Procedures for Description and Measurement of Environmental Sound—Part 4: Noise Assessment and Prediction of Long-term Community Response* (American National Standards Institute, New York).

ANSI (**2008**). ANSI S12.2. *Criteria for Evaluating Room Noise* (American National Standards Institute, New York).

Attenborough, K., Taherzadeh, S., Bass, H E., Di, X., Raspet, R., Becker, G. R., Güdesen, A., Chrestman, A., Daigle, G. A., L'Espérance, A., Gabillet, Y., Gilbert, K. E., Li, Y. L., White, M. J., Naz, P., Noble, J. M., and van Hoof, H. A. J. M. (**1995**). "Benchmark cases for outdoor sound propagation models," J. Acoust. Soc. Am. **97**(1), 173–191.

Boue, M. (**2007**). "Long-range sound propagation over the sea with application to wind turbine noise," Swedish Energy Agency, Report 21597-3, p. 68.

Bowman, J. R., Baker, G. E., and Bahavar, M. (**2005**). "Ambient infrasound noise," Geophys. Res. Lett. **32**, L09803, https://doi.org/10.1029/2005GL022486.

Broner, N. (**2010**). "A simple criterion for low frequency noise emission assessment," J. Low Freq. Noise Vib. Active Control **29**(1), 1–14.

Buck, S., Oerlemans, S., and Palo, S. (**2018**). "Experimental validation of a wind turbine turbulent inflow noise prediction code," AIAA J. **56**(4), 1495–1506.

Daigle, G., and Stinson, M. (**2005**). "Attenuation of environmental noise: Comparing the predictions of ISO 9613-2 and theoretical models," in *Proceedings of Internoise 2005*.

Daigle, G., and Stinson, M. (**2014**). "Analysis, modeling, and prediction of infrasound and low frequency noise from wind turbine installation, phase 1: PEI site, final report," MG Acoustics Report for Health Canada, 81 pp.

Daigle, G., and Stinson, M. (**2016**). "Prediction of infrasound and low frequency sound from a wind turbine installation," MG Acoustics Report for Health Canada, 15 pp.

Di, X., and Daigle, G. A. (**1994**). "Prediction of noise propagation during upward refraction above ground," in *Proceedings of Inter-noise 94*, Yokohama, pp. 563–566.

Edwards, W. (**2015**). "Analysis of measured wind turbine seismic noise generated from the Summerside Wind Farm, Prince Edward Island," Natural Resources Canada Report, http://geoscan.nrcan.gc.ca/starweb/geoscan/servlet.starweb?path=geoscan/fulle.web&search1=R=296443 (Last viewed April 9, 2018).

Environment Canada (**2016**). "Historical data," http://climate.weather.gc.ca/historical_data/search_historic_data_e.html (Last viewed April 9, 2018).

Eurasto, R. (**2006**). "NORD2000 for road traffic noise prediction, Weather classes and statistics," Technical Research Centre of Finland, VTT-R-02530-06.

Fisheries and Oceans Canada (**2016**). "Meteorological Data," http://www.isdm.gc.ca/isdm-gdsi/azmp-pmza/met/index-eng.asp?lev=2 (Last viewed April 9, 2018).

Friman, M. (**2011**). "Directivity of sound from wind turbines: A study on the horizontal sound radiation pattern from a wind turbine," MaSc thesis, Department of Aeronautical and Vehicle Engineering, The Marcus Wallenberg Laboratory for Sound and Vibration Research, http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.692.4197&rep=rep1&type=pdf (Last viewed June 26, 2018).

Garces, M., Hetzer, C., Merrifield, M., Willis, M., and Aucan, J. (**2003**). "Observations of surf infrasound in Hawaii," Geophys. Res. Lett. **30**(24), 2264, https://doi.org/10.1029/2003GL018614.

Garces, M., and Willis, M. (**2006**). "Modeling and characterization of microbarom signals in the Pacific," Defense Threat Reduction Agency, Technical Report, DTRA-TR-04-24, pp. OCE 5-1–OCE 5-3.

GeoBase Canadian Digital Elevation Data 1945 2010 (**2010**). Ministry of Natural Resources, Ottawa, ON, https://open.canada.ca/data/en/dataset/7f245e4d-76c2-4caa-951a-45d1d2051333 (Last viewed April 9, 2018).

Gilbert, K. E., and Di, X. (**1993**). "A Fast Green's function method for one-way sound propagation in the atmosphere," J. Acoust. Soc. Am. **94**(4), 2343–2352.

Hansen, K., Hessler, G., Hansen, C., and Zajamsek, B. (**2015**). "Precision of infrasound and low frequency noise propagation for modern turbines—a proposed supplement to ISO 9613-2," in *Proceedings of the 6th International Meeting on Wind Turbine Noise*, Glasgow.

Heimann, D., Bakermans, M., Defrance, J., and Kuhner, D. (**2007**). "Vertical sound speed profiles determined from meteorological measurements near the ground," Acta Acust. Acust. **93**, 228–240.

Heimann, D., and Salomons, E. M. (**2004**). "Testing meteorological classifications for the prediction of long-term average sound levels," Appl. Acoust. **65**, 925–950.

Hidaka, T., Kageyama, K., and Masuda, S. (**1985**). "Sound propagation in the rest atmosphere with linear sound velocity profile," J. Acoust. Soc. Jpn. (E) **6**(2), 117–125.

Hubbard, H. H., and Shepherd, K. P. (**1991**). "Aeroacoustics of large wind turbines," J. Acoust. Soc. Am. **89**(6), 2495–2508.

IEC 61400-11 (**2012**). "Wind turbine generator systems—Part 11: Acoustic noise measurement techniques," 3rd ed. (International Electrotechnical Commission, Geneva).

ISO 226 (**2003**). "Acoustics. Normal equal-loudness-level contours" (International Organization for Standardization, Geneva).

ISO 7196 (**1995**). "Acoustics, frequency-weighting characteristic for infrasound measurements" (International Organization for Standardization, Geneva).

ISO 9613-1 (**1993**). "Acoustics, attenuation of sound during propagation outdoors. Part 1: Calculation of the absorption of sound by the atmosphere" (International Organization for Standardization, Geneva).

ISO 9613-2 (**1996**). "Acoustics—Attenuation of sound during propagation outdoors—Part 2: General method of calculation" (International Organization for Standardization, Geneva).

ISO/IEC Guide 98-3 (**2008**). "Uncertainty of measurement—Part 3: Guide to the expression of uncertainty in measurement" (International Organization for Standardization, Geneva).

Johansson, L. (**2003**). "Sound propagation around off-shore wind turbines," Ph.D. dissertation, King Tekniska Hogskolan, Stockholm, p. 87.

Jónsson, G. B., and Jacobsen, F. (**2008**). "A comparison of two engineering models for outdoor sound propagation: Harmonoise and Nord2000," Acta Acust. united Acust. **94**(2), 282–289.

Keith, S. E., Feder, K., Voicescu, S. A., Soukhovtsev, V., Denning, A., Tsang, J., Broner, N., Leroux, T., Richarz, W., and van den Berg, F. (**2016a**). "Wind turbine sound pressure level calculations at dwellings," J. Acoust. Soc. Am. **139**(3), 1436–1442.

Keith, S. E., Feder, K., Voicescu, S. A., Soukhovtsev, V., Denning, A., Tsang, J., Broner, N., Richarz, W., and van den Berg, F. (**2016b**). "Wind turbine sound power measurements," J. Acoust. Soc. Am. **139**(3), 1431–1435.

Le Pichon, A., Ceranna, L., and Vergoz, J. (**2012**). "Incorporating numerical modeling into estimates of the detection capability of the IMS infrasound network," J. Geophys. Res. **117**, D05121, https://doi.org/10.1029/2011JD016670.

Lee, S. W., Bong, N., Richards, W. F., and Raspet, R. (**1986**). "Impedance formulation of the fast field program for acoustic wave propagation in the atmosphere," J. Acoust. Soc. Am. **79**(3), 628–634.

L'Espérance, A., Herzog, P., Daigle, G. A., and Nicolas, J. R. (**1992**). "Heuristic model for outdoor sound propagation based on an extension of the geometrical ray theory in the case of a linear sound speed profile," Appl. Acoust. **37**, 111–139.

L'Esperance, A., Nicolas, J., Wilson, D. K., Thomson, D. W., Gabillet, Y., and Daigle, G. (**1993**). "Sound propagation in the atmospheric surface layer: Comparison of experiment with FFP predictions," Appl. Acoust. **40**, 325–346.

Makarewicz, R. (**2011**). "Is a wind turbine a point source?," J. Acoust. Soc. Am. **129**(2), 579–581.

Marcillo, O., Arrowsmith, S., Blom, P., and Jones, K. (**2015**). "On infrasound generated by wind farms and its propagation in low-altitude tropospheric waveguides," J. Geophys. Res. Atmos. **120**(19), 9855–9868, https://doi.org/10.1002/2014JD022821.

Michaud, D. S., Feder, K., Keith, S. E., Voicescu, S. A., Marro, L., Than, J., Denning, A., McGuire, D., Bower, T., Lavigne, E., Murray, B. J., Weiss, S. K., and van den Berg, F. (**2016**). "Exposure to wind turbine noise: Perceptual responses and reported health effects," J. Acoust. Soc. Am. **139**(3), 1443–1454.

Monin, A. S., and Obukhov, A. M. (**1954**). "Basic laws of turbulent mixing in the atmosphere near the ground," Tr. Akad. Nauk SSSR Geofiz. Inst. **24**(151), 163–187.

Okada, Y., Uemuira, T., Yoshihisa, K., and Iwase, T. (**2016**). "Study on empirical formula for the sound directivity around a wind turbine," in *Proceedings of Internoise 2016*, pp. 7821–7829.

ONMOE (**1978**). "Model municipal noise control by-law—Final report," Ontario Ministry of the Environment.

Plovsing, B. (**2006a**). "Nord2000. Comprehensive outdoor sound propagation model. Part 1: Propagation in atmosphere without significant refraction," Delta Acoustics &Vibration Report AV 1849/00 (March).

Plovsing, B. (**2006b**). "Nord2000. Comprehensive outdoor sound propagation model. Part2: Propagation in an atmosphere with refraction," Delta Acoustics &Vibration Report AV 1851/00 (March).

Raspet, R., Lee, S. W., Kuester, E., Chang, D. C., Richards, W. F., Gilbert, R., and Bong, N. (**1985**). "Fast-field program for a layered medium bounded by complex impedance surfaces," J. Acoust. Soc. Am. **77**(2), 345–352.

Salomons, E., van Maercke, D., Defrance, J., and de Roo, F. (**2011**). "The Harmonoise sound propagation model," Acta Acust. united Acust. **97**, 62–74.

SEPA (**2012**). "Ljud från vindkraftverk" ("Noise from wind turbines"), Report 6241 version 3.0 (in Swedish), Swedish Environmental Protection Agency, Stockholm.

Sondergaard, B., and Plovsing, B. (**2005**). "Noise from off-shore wind turbines," Danish Ministry of Environment, Project No. 1016, p. 31.

Styles, P., Stimpson, I., Toon, S., England, R., and Wright, M. (**2005**). "Monitoring of low frequency noise and vibrations from windfarms, Recommendations on the siting of windfarms in the vicinity of Eskdalemuir, Scotland," Keele University Report.

Sutherland, L. C., and Bass, H. E. (**2004**). "Atmospheric absorption in the atmosphere up to 160 km," J. Acoust. Soc. Am. **115**(3), 1012–1032.

Sutherland, L. C., and Bass, H. E. (**2006**). "Erratum: Atmospheric absorption in the atmosphere up to 160 km" [J. Acoust. Soc. Am. **115**(3), 1012–1032], J. Acoust. Soc. Am. **120**(5), 2985.

Turnbull, C., Turner, J., and Walsh, D. (**2012**). "Measurement and level of infrasound from wind farms and other sources," Acoust. Australia **40**(1), 45–50.

van Maercke, D., and Defrance, J. (**2007**). "Development of an analytical model for outdoor sound propagation within the harmonoise project," Acta Acust. Acust. **93**(2), 201–212.

Whitaker, R. W. (**1995**). "Infrasonic monitoring," *17th Annual Seismic Research Symposium*, LANL, Scottsdale, AZ.

Willshire, W. (**1985**). "Long range downwind propagation of low-frequency sound," NASA TM 86409 (April).

Willshire, W., and Zorumski W. (**1987**). "Low-frequency acoustics propagation in high winds," in *Proceedings Noise-Con*, Vol. 87, pp. 275–280.

Zajamšek, B., Hansen, K. L., Doolan, C. J., and Hansen, C. H. (**2016**). "Characterisation of wind farm infrasound and low-frequency noise," J. Sound Vib. **370**, 176–190.