Noise Monitoring in the Vicinity of the Waterloo Wind Farm

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1 Introduction

This report details independent noise measurements and their analysis taken in the vicinity of the Waterloo Wind Farm during the period 9/4 – 22/6, which is the same period as the study undertaken by the EPA and reported in EPA (2013). Measurements were taken outside of as well as inside a number of residences. Due to the potential for data contamination by background noise during the day, only data measured between midnight and 5am are reported here, as during those hours, the dominant noise source was generally the wind farm. The following sections of this report detail the measurement equipment, measurement procedures, data analysis and data interpretation, followed by a conclusion summarising the results detailed in the rest of the report.

The data analysis and interpretation comprises four sections:

- overall levels averaged over 10-minutes for all night-time data collected at each residence;
- unweighted third-octave spectra and overall levels for the shutdown periods;
- unweighted third-octave spectra and narrowband spectra for measurement times corresponding to noise diary entries; and
- unweighted and A-weighted third-octave spectra for measurements which exceeded 40 dB(A).

2 Measurement Details

Three B&K 4955 microphones were used for the indoor measurements. These microphones have a low noise floor of 6.5 dB(A) and a flat frequency response down to 6 Hz. While these microphones do not have a flat frequency response below 6 Hz, they are still capable of measuring the blade-pass frequency and harmonics (Hansen, 2013). The microphones were connected to LAN-XI hardware and continuous 10-minute recordings were made using Pulse software. The average sound pressure level of the three microphones was calculated in accordance with the Danish guidelines for indoor low-frequency noise measurements (Jakobsen, 2001). This average includes one microphone positioned in the room corner. In this position, the maximum sound pressure level would be measured since this is an anti-node for all room response modes. A single GRAS 40AZ / SV 17 microphone was connected to a SVAN 979 sound level meter. This microphone was used as a back-up and check for the indoor measurements made with the Pulse system.

The outdoor measurements were made using GRAS 40AZ / SV 12L microphones connected to a SVAN 958 sound level meter, which measured continuously over 10-minute intervals. The microphones have a noise floor of 17 dB(A) and a flat frequency response down to 0.8 Hz. Hemispherical secondary windshields were used to minimise wind-induced noise experienced by the outdoor microphones, and they were designed to be consistent with the IEC 61400-11 standard, which specifies the use of these secondary windshields for measurements close to a wind turbine. A spherical secondary windshield and box windshield with specifications described in Hansen (2013) were also used for comparison but these results are only presented in the narrowband analysis in Section 6.2. Wind speed and direction were measured at heights of 1.5 m and 10 m using Davis Vantage Vue and Vantage Pro weather stations, respectively. The weather measurements were collected in 5-minute intervals and then the 10-minute average was calculated during post-processing.

3 Guidelines

It is well known that wind farm noise is dominated by low-frequency energy (Moller & Pedersen, 2011), particularly at large distances from the wind farm, where the high-frequency noise has been more attenuated than the low-frequency noise. As such, a number of different weighting functions have been applied to the data in Section 4 to highlight different characteristics of the noise. A detailed description of these weightings and their applications is given in the report by the EPA (2013). This section provides a brief analysis of the limitations of some of these weighting functions in the context of wind turbine noise. Additionally, some drawbacks of the current SA EPA guidelines (EPA, 2009) are discussed and recommendations for improvements are suggested.

In South Australia, compliance of a wind farm is determined based on the applicable outdoor limit specified in the SA EPA guidelines (2009). Most of the measurement locations detailed in this report correspond to “rural industrial” zones where the allowable limit is 40 dB(A). One of the township locations is situated in an area which has been zoned “township” according to the Clare and Gilbert Valleys Council regulations. For lack of additional information, it is assumed that this translates to “rural living” in the context of the SA EPA guidelines (2009), which has a corresponding outdoor limit of 35 dB(A). According to the EPA guidelines (2009), a compliance analysis requires collection of over 2,000 data points, with 500 data points recorded for the worst-case wind direction. For the measurements outlined in this report, such a large amount of data were not collected at any one location, however it was still considered valuable to plot a regression curve to illustrate the degree of compliance over short periods as well. In any case, the use of night-time data is expected to reduce the degree to which data are contaminated by extraneous sources, thus giving a reasonable estimate of the degree to which the wind farm is compliant.

The SA EPA guidelines also specify use of the L_{A90} metric, which is the A-weighted noise level that is exceeded 90% of the time. It should be noted that wind farm noise can be significantly underestimated using L_{A90} levels due to the unsteady nature of the noise. Hence, the L_{Aeq}, which is the energy average of the noise, is considered to be a more realistic representation of the actual noise level attributed to the wind farm, particularly between midnight and 5am when there are very few other noise sources of a similar level to the wind farm noise.

Despite the fact that low-frequency noise has been identified as a potential issue associated with wind turbine operation, the SA EPA guidelines (2009) do not provide guidance for acceptable levels of low-frequency noise and infrasound, even though there are several recommendations available in the literature. For example, the C-weighting can be used to provide an indicator of the presence of low-frequency noise. According to Broner (2010), a night-time limit of 60 dB(C) is recommended, and this limit was included in the NSW draft guidelines (2011). Low-frequency noise can also be identified by finding the difference between the overall C-weighted and A-weighted levels. When $L_{Ceq} - L_{Aeq} > 20$, a potential low-frequency noise problem is indicated, and Broner and Leventhall (1983) and DIN 45680 (1997) would recommend further investigation into the time-dependent low-frequency noise characteristics including noise fluctuations, spectral balance and amplitude modulation.

The G-weighting is used to indicate the level of infrasound. According to ISO 7196 (1995) and DIN 45680 (1997), the audible threshold for the overall G-weighted noise level is 85 dB(G). On the other hand, this does not preclude the possibility that lower levels of infrasound will have an effect on people (Salt & Lichtenhan, 2014).

The SA EPA guidelines (2009) suggest that the indoor A-weighted noise level should not exceed 30 dB(A). According to the World Health Organisation night-time guidelines (WHO, 2009), the no observed effect limit for *outdoor* noise is 30 dB(A). To quantify the low-frequency contribution to the indoor noise, it is useful to refer to the Danish guidelines for indoor low-frequency noise (Danish EPA, 1997) and the UK Department of Food and Rural Affairs criteria (DEFRA, 2005). The Danish limit considers A-weighted levels in the frequencies from 10 Hz to 160 Hz and the limit is the calculated average of the sound pressure level measured at three different locations in a room. According to the Danish guidelines, the indoor noise level, $L_{pA,lf}$ in the frequency range from 10 Hz to 160 Hz should not exceed 20 dB(A). The DEFRA criteria are frequency dependent and also span the frequency range from 10 Hz – 160 Hz. The allowable limits for each third-octave frequency bin in this range are specified in the relevant report (DEFRA, 2005). The specified limits can be relaxed for steady noise and for daytime measurements but the measurements in this report did not fall into either of these categories. It is well-known that wind farm noise is an unsteady noise source due to sudden changes in wind speed/direction, inflow turbulence, wind shear (van den Berg, 2005) and directivity (Oerlemans & Shepers, 2009). It has also been found that wind farm noise is modulated at the blade-pass frequency (Hansen *et al.*, 2013), which causes a periodic variation in the loudness of the sound.

It is worth noting that wind farm compliance according to the SA EPA guidelines is based on a regression line fitted to 2000 or more data points plotted on a graph of noise level (dBA) (y-axis) vs hub height wind speed (x-axis). Each data point is a 10-minute average, which means that the influence on people of a noise source that is highly variable in nature will be underestimated. In addition, many 10-minute average data points are above the acceptable 35 or 40 dB(A) requirement and as compliance is based on the regression line only, these times of relatively high noise level are ignored. In other words, compliance with the EPA guidelines does not mean that noise levels will never exceed the recommended limits – in fact, they can exceed the recommended limits many times as can be seen by the graphs shown in this report. Furthermore, the 10-minute average values are lower than the peak values, which means that the wind farm could generate high levels of intermittent noise and still be compliant.

It is also important to recognise that thresholds of audibility are not dependent on the 10-minute average of the root mean square (rms) value of the noise signal alone. This type of analysis ignores any difference in character between the measured noise and the noise used in the laboratory to determine threshold levels. The main differences in character that are important include the presence of multiple harmonics of the blade passage frequency and the crest factor of the noise. The crest factor is the ratio of the peak noise level to the average (or rms) noise level. The measured average noise levels for wind farm noise have been shown to contain peaks that are up to 20 dB above the reported average level. Even for "compliant" wind farms, such peaks are well above the levels required to disturb sleep (according the 2009 WHO document, "Night Noise Guidelines for Europe"). It is also worth noting that traffic noise, on which the WHO document on night noise levels is based, is not characterised by such high crest factors and thus has less potential for disturbing sleep. Nevertheless, this is an area of future work for our research group and the purpose of this report is to provide an analysis similar to that carried out in the EPA study so that comparison can be made between the two sets of results.

4 Overall Noise Levels

The following section presents data that were measured at the same residences as the EPA study (EPA, 2013), as well as three additional residences. The North East residence is not included in the analysis as we were unable to measure inside at this location. A number of weighting functions have been applied to the data and where applicable, a linear regression curve has been included. The DEFRA criteria and the Danish guidelines for indoor low-frequency noise have only been applied to the indoor data, as they are not considered relevant for outdoor noise.

The figures presented in this section show data plotted against the wind speed at a height of 10 m in the left hand column and data plotted against the wind speed at hub height in the right hand column. Data points shown in red correspond to times when the residence was downwind from the proposed wind farm, according to the definition that downwind is ±45° from the direction of the residence relative to the wind farm. Data points shown in green indicate times where the wind speed at a height of 1.5 m was greater than 5 m/s. For such wind speeds, noise measurements can be contaminated by wind-induced noise. The sources of wind-induced noise are pseudo-noise and acoustic noise. Pseudo-noise is caused by turbulent pressure fluctuations and vortex shedding incident on the microphone which lead to false indications of the sound pressure level whereas wind-induced acoustic noise arises when objects such as tree branches and leaves are put in motion by the wind. Pseudo-noise is only relevant for outdoor measurements but wind-induced acoustic noise is relevant to both indoor and outdoor measurements. Both indoor and outdoor measurements taken during periods of rain have been discarded from the analysis.

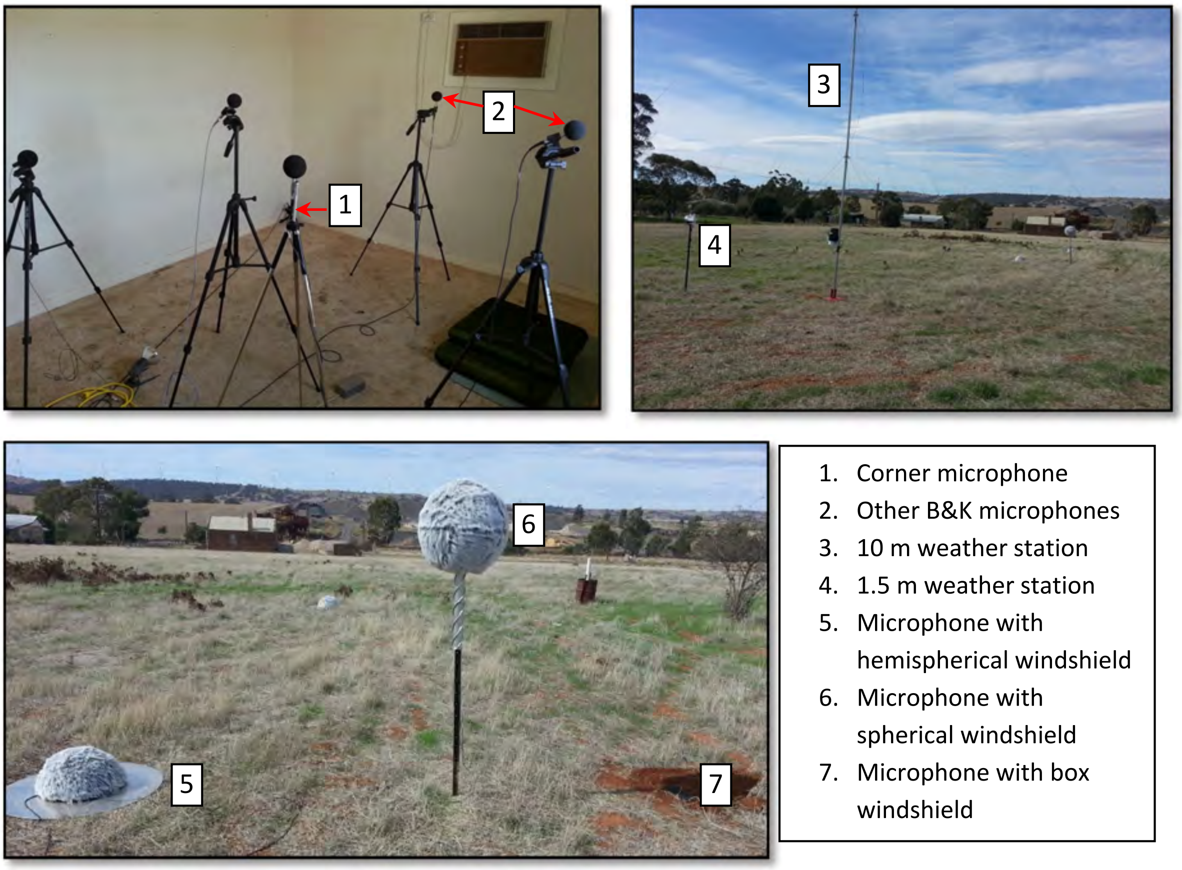
In this section, all plotted data corresponds to night-time measurements made between 12 am and 5 am. During the night, people are trying to sleep and this time also represents the greatest contrast between ambient noise and wind turbine noise, due to the absence of other sources such as traffic and farming machinery. These times were also selected to minimise contamination from noise sources other than the wind farm.

4.1 Township site

The residence at which the following measurements were taken is the same as the one used in the EPA study. The closest wind turbine to this measurement site is ‘CD’, which is 3.5 km from the residence. The downwind direction from the closest wind turbine to the residence is between 43° and 133°. It is estimated that this residence was built in the early 1900s. The walls are constructed from 350 mm thick stone/cement brick, the windows are a small-medium single-pane wood-framed sash design and the roof is constructed from corrugated sheet steel. The ceiling consists of plaster panels, where timber battens cover the joins and the ceiling space has “Cool and Cosy” recycled paper insulation.

The indoor instruments were located in the room closest to the wind farm, which has one window which faces towards the wind farm. For the duration of the measurements, the residence was unoccupied and no electrical appliances were operating inside, with the exception of our monitoring equipment. The zoning for this residence is “rural industrial” since it has been classified as a “primary production” area by the Clare and Gilbert Valleys Council.

The instrumentation set-up for the measurements at this residence is shown in Figure 1. The microphones used for the indoor averaging are labelled 1 and 2. The outdoor instrumentation was located about 50 m from the residence to avoid reflective surfaces and also to avoid shielding from the wind farm. The wind turbines are clearly visible in the background from the open field in which the measurements were taken.



1. Corner microphone
2. Other B&K microphones
3. 10 m weather station
4. 1.5 m weather station
5. Microphone with hemispherical windshield
6. Microphone with spherical windshield
7. Microphone with box windshield

Figure 1 – Instrumentation set-up at Township residence

The results presented in the following analysis are the amalgamation of four data sets which were acquired from 1st May – 3rd June 2013. The outdoor results shown in Figure 2 were obtained using a single microphone mounted on a ground board and protected from the wind by a secondary hemispherical windshield. The data plotted in Figure 3 and Figure 4 show the average noise levels for the three indoor microphones pictured in Figure 1.

For the outdoor A-weighted data, a linear regression fit has been applied to both figures and it can be seen that there is a better regression fit when the data are plotted against the wind speed at a height of 10 m. The greater spread which occurs when the data are plotted against the wind speed at hub height can be attributed to the fact that the A-weighted noise levels are consistently higher for downwind conditions. On the other hand, the closer regression fit, obtained by plotting the data against the wind speed at a height of 10 m, also suggests that there is a correlation between the local wind speed and the A-weighted noise level. Nevertheless, all data points exceeding the outdoor limit of 40 dB(A) occurred when the residence was downwind from the wind farm and for all data points except one, the wind speed at a height of 1.5 m was less than 5 m/s. In addition, all measurements with identified vehicle and animal noise sources have been eliminated from the results. However, despite the large number of data points which exceed the outdoor limit, the wind farm would be deemed compliant based on the results of a linear regression fit.

The outdoor C-weighted results shown in Figure 2 (c) and (d) indicate that the levels are higher when the residence is downwind from the wind farm. On the other hand, the L_{Ceq} exceeds the 60 dB(C) level by only a small amount and thus does not indicate a low-frequency noise problem according to this metric.

Subtracting the overall A-weighted outdoor level from the overall C-weighted outdoor level gives the results presented in Figure 2 (e) and (f). It is evident that for the majority of cases, exceedances occurred when the residence was downwind from the wind farm. While there is a large spread in the data, there are many instances where the limit of $L_{Ceq} - L_{Aeq} = 20$ dB is exceeded, indicating that there is a low-frequency noise problem by this metric, and this occurred mainly for downwind conditions.

The G-weighted outdoor levels shown in Figure 2 (g) and (h) and Figure 4 (a) and (b) indicate that the L_{Geq} is less than 70 dB(G) for all measurements, which is well below the publicised hearing threshold of 85 dB(G) (ISO 7196, 1995). This may imply that the infrasound would not be audible to a person with normal hearing. However, it does not mean that the infrasound is not detectable (Salt & Lichtenhan, 2014), especially when the crest factor (ratio of peak to rms) of the sound is considered. This is because the threshold levels were determined in the laboratory for single, steady tones which are very different in character to wind farm infrasound and low-frequency sound.

The A-weighted levels measured indoors are shown in Figure 3 (a) and (b). The measured levels of indoor noise are as low as 5 dB(A), which shows that in some instances, there is very little masking noise. On other occasions, the indoor noise levels are close to 30 dB(A), particularly where the wind speed at hub height exceeds 14 m/s and the residence is downwind from the wind farm. On these occasions, the wind speed at the residence at a height of 10 m can also be relatively high, as shown in Figure 3 (a). Nevertheless, the wind speed at the residence at a height of 1.5 m is less than 5 m/s for all data points except one, which indicates that the wind was not causing significant buffeting of the house during these measurements. Hence, the high levels of indoor noise can be attributed to the wind farm with a reasonable degree of confidence.

The difference between the overall indoor A-weighted level (L_{Aeq}) and the indoor A-weighted level exceeded for 90% of the time (L_{A90}) is shown in Figure 3 (c) and (d). The average difference between these metrics was calculated to be 3.3 dB(A). However, even between the hours of 12am and 5am, where the contribution from extraneous noise sources is expected to be minimal, this difference can be as high as 9 dB(A). There is also an increasing trend in the difference as both the hub height wind speed and the wind speed at a height of 10 m increases. It should be noted that all audio files which were contaminated by vehicle noise were eliminated from this analysis. Also, the wind speed at a height of 1.5 m measured at the residence was only greater than 5 m/s for one data point, indicating that noise caused by the wind buffeting against the house would have been minimal. Therefore, it is probable that the large difference between the L_{Aeq} and the L_{A90} is caused by wind turbine noise, which can be highly variable with time depending on the atmospheric conditions. If this is the case, using the L_{A90} to determine compliance would lead to erroneous results.

Another feature of interest is that the difference between the L_{Ceq} and L_{Aeq} is higher for the indoor results in comparison to the outdoor results, as shown in Figure 3 (g) and (h). This difference can be as high as 30 dB, which reflects the larger bias towards noise at lower frequencies which occurs indoors. It is well known that noise weighted to lower frequencies would be more annoying than a well-balanced spectrum (Blazier, 1997).

In addition, the Danish guideline limit of 20 dB(A) is exceeded on a number of occasions as indicated in Figure 4 (c-d). In every case, the residence is downwind from the wind farm but the wind speed ranges from 1 – 7 m/s at a height of 10 m. The DEFRA criteria are also not met for several measurements, as shown in Figure 4 (e-f). In these cases, only 92% of third octave bands show acceptable levels and this occurs mainly for downwind conditions over a range of wind speeds from 1 – 7 m/s at a height of 10 m.

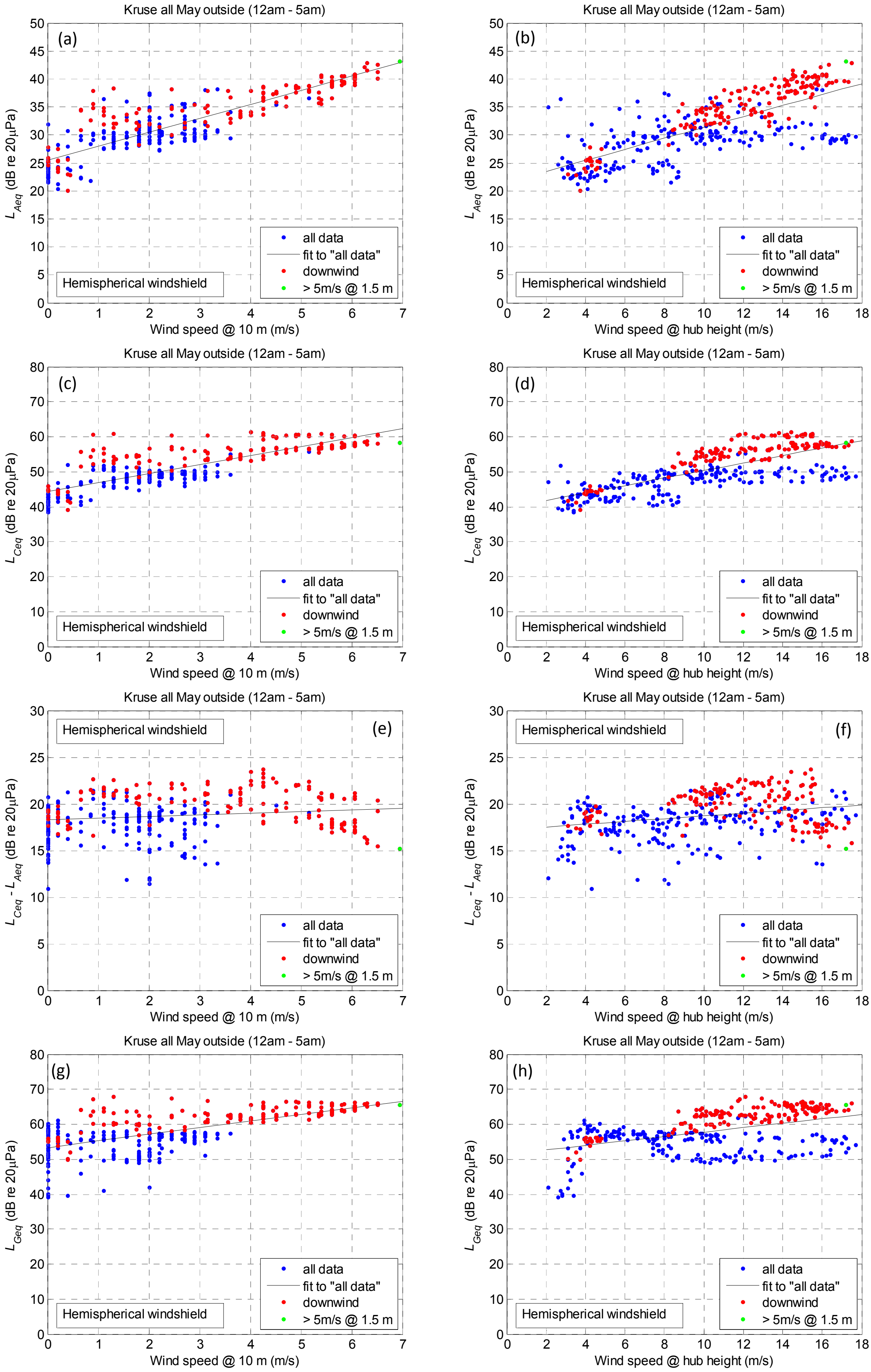


Figure 2 – Outdoor measurement results for Township residence.

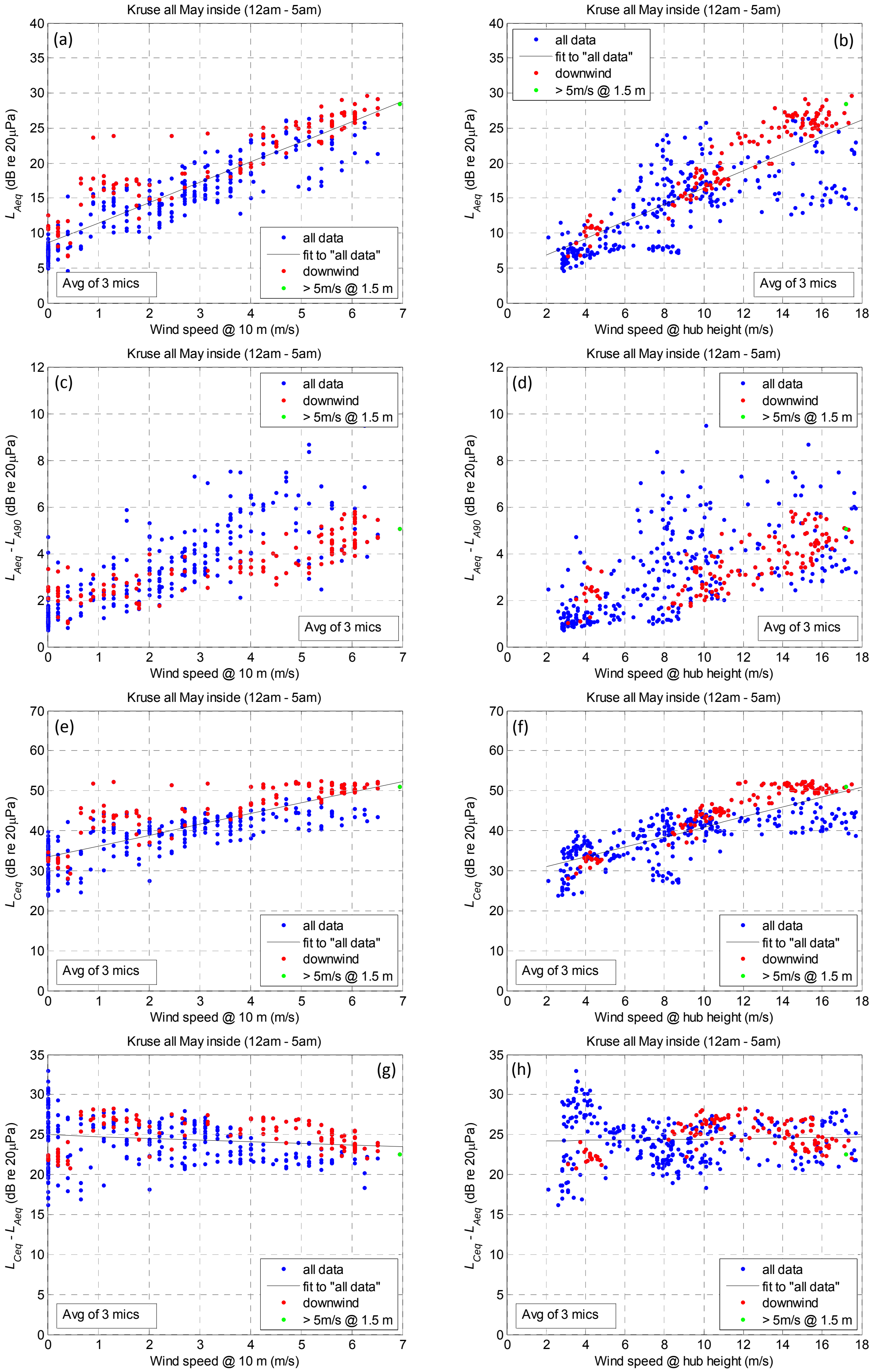


Figure 3 – Indoor measurement results for Township residence (first set).

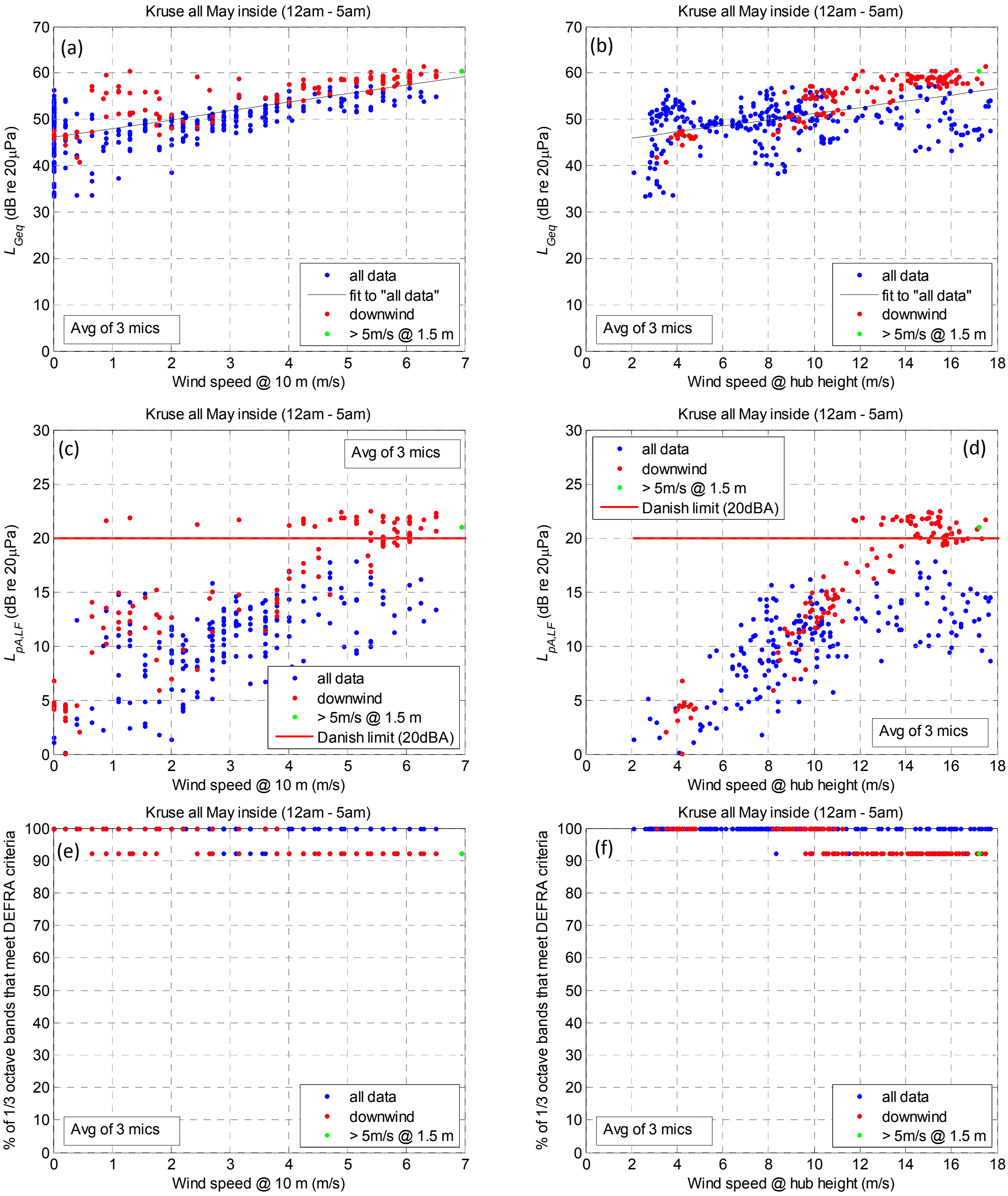
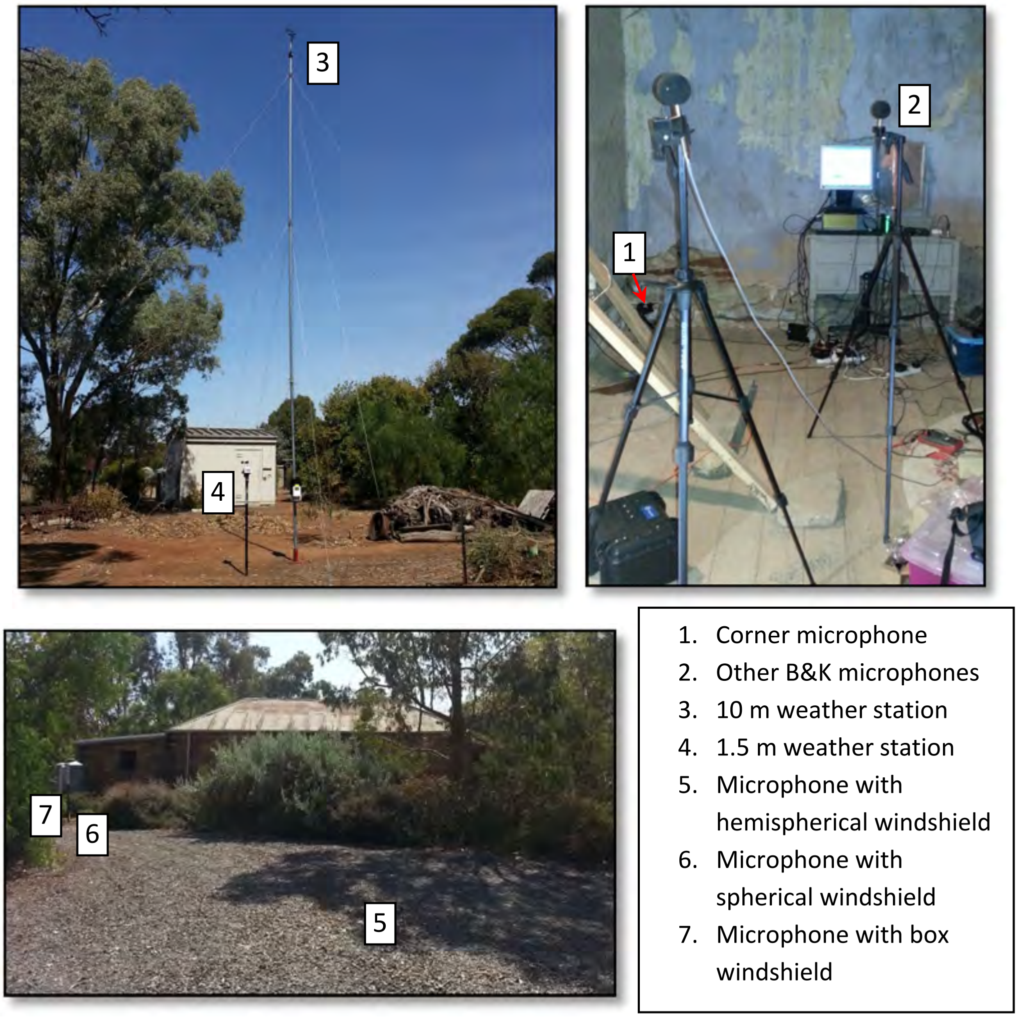


Figure 4 – Indoor measurement results for Township residence (second set).

4.2 Township site 2

The second Township site is located in the centre of Waterloo and was not used in the EPA study. The closest wind turbine to this measurement site is ‘BA’, which is 3.4 km from the residence. The downwind direction from the closest wind turbine to the residence is between 43° and 133°. It is assumed that this location is classified as a “rural living” zone since it is considered as a “township” zone according to the Clare and Gilbert Valleys Council regulations. Therefore the allowable limit for wind farm noise at this residence is 35 dB(A). It is estimated that this residence was built in the late 1800s to early 1900s. The walls are constructed from 400-500 mm thick stone, the roof consists of corrugated sheet steel and the ceiling material is matchboard. There is no insulation in the walls or ceiling space of this residence. The indoor instruments were located in the room closest to the wind farm, which has one window which faces towards the wind farm. This window is covered with wooden boards. For the duration of the measurements, the residence was unoccupied and no electrical appliances were operating inside with the exception of our monitoring equipment. The instrumentation set-up for this residence is shown in Figure 5.



1. Corner microphone
2. Other B&K microphones
3. 10 m weather station
4. 1.5 m weather station
5. Microphone with hemispherical windshield
6. Microphone with spherical windshield
7. Microphone with box windshield

Figure 5 – Instrumentation set-up at Township 2 residence.

The outdoor microphones and weather stations were located as far as possible from nearby trees. Although the outdoor microphones are not pictured in Figure 5, their positioning has been indicated.

One of the B&K microphones used for the indoor averaging is also not visible in the pictures. The corner B&K microphone labelled 1 was positioned in the room corner closest to the wind farm.

The results presented in the following analysis were collected over one week from 9th-16th April 2013. The outdoor results shown in Figure 6 were obtained using a single microphone mounted on a ground board and protected from the wind by a secondary hemispherical windshield. The data plotted in Figure 7 and Figure 8 show the average noise levels for the three indoor microphones pictured in Figure 5.

For the outdoor A-weighted results presented in Figure 6 (a) and (b), it can be seen that there were numerous occasions when there was no wind at the residence at a height of 10 m and there was wind at hub height. In these instances, the overall A-weighted SPL varied by at least 15 dB(A). This indicates that between the hours of 12 am and 5 am, a source other than wind-induced noise on the microphone caused a variation in ambient noise level of at least 15 dB(A) for these cases. It is also evident in Figure 6 (a) and (b) that the measured noise level exceeded 35 dB(A) on a number of occasions. It should be noted that all measurements which contained vehicle or animal noise sources have been eliminated from the results. In addition, the wind speed measured at the residence at a height of 1.5 m did not exceed 1.3 m/s for any measurements, which indicates that wind-induced noise on the outdoor microphones would have been minimal. Nevertheless, the regression curve plotted in Figure 6 (b), shows that the wind farm would be compliant according to the 35 dB(A) limit, despite the fact that many data points lie above this curve. It can also be seen that the majority of points lying above the regression line are associated with downwind conditions. Thus, it is reasonable to assume that the increased levels can be attributed to the wind farm. It is well known that wind farm noise is generally more significant in downwind conditions (Van den Berg, 2005), which further confirms that the wind farm was the major contributor to the measured noise levels.

The outdoor C-weighted results shown in Figure 6 (b) and (c) indicate that the levels are higher when the residence is downwind from the wind farm. On the other hand, the L_{Ceq} exceeds the 60 dB(C) level by only a small amount and thus does not indicate a low-frequency noise problem according to this metric.

There is a large spread in the data for $L_{Ceq} – L_{Aeq}$, shown in Figure 6 (e) and (f), which is most significant when the wind speed at a height of 10 m at the residence is zero. As the cut-in wind speed for Vestas v90 wind turbines is 3.5 m/s (Vestas, n.d.), reference to Figure 6 (f) indicates that the closest wind turbine would have been rotating for the majority of the measurements. There are a number of occasions where $L_{Ceq} – L_{Aeq} > 20$ dB, once again indicating the possibility of a low-frequency issue.

The G-weighted outdoor and indoor levels shown in Figure 6 (g) and (h) and Figure 8 (a) and (b) indicate that the $L_{Geq} < 66$ dB(G) for all measurements, which is lower than the 85 dB(G) audible threshold (ISO 7196, 1995). This may imply that the infrasound would not be audible to a person with normal hearing. However, as discussed in Section 4.1, this does not mean that the infrasound is not detectable (Salt & Lichtenhan, 2014), especially when the crest factor (ratio of peak to rms) of the sound is considered.

The indoor A-weighted levels shown in Figure 7 (a) and (b) were relatively low at this residence, which is related to the fact that the wind speed at hub height did not reach the rated wind speed of the turbines of 15 m/s (Vestas, n.d.). Despite this, the levels varied by over 10 dB(A) indoors even though there was minimal wind at the residence.

The difference between the overall indoor A-weighted level (L_{Aeq}) and the indoor A-weighted level exceeded for 90% of the time (L_{A90}) is shown in Figure 7 (c) and (d). The average difference between these metrics was calculated to be 2.4 dB(A). However, between the hours of 12am and 5am, where the contribution from extraneous noise sources is expected to be minimal, this difference can be as high as 9 dB(A). It should be noted that all audio files which were contaminated by vehicle noise were eliminated from this analysis. Therefore, it is probable that the large difference between the L_{Aeq} and the L_{A90} is caused by wind turbine noise, which can be highly variable with time depending on the atmospheric conditions. If this were the case, using the L_{A90} to determine compliance would lead to erroneous results.

Once again the indoor $L_{Ceq} – L_{Aeq}$ shown in Figure 7 (g) and (h) is greater than that measured outdoors. On the other hand, the Danish low-frequency guidelines was met on all occasions at this residence as indicated in Figure 8 (c) and (d) and the DEFRA criteria were satisfied in the majority of cases, as depicted in Figure 8 (e) and (f). In those cases where the DEFRA criteria were not satisfied, the residence was downwind from the wind farm.

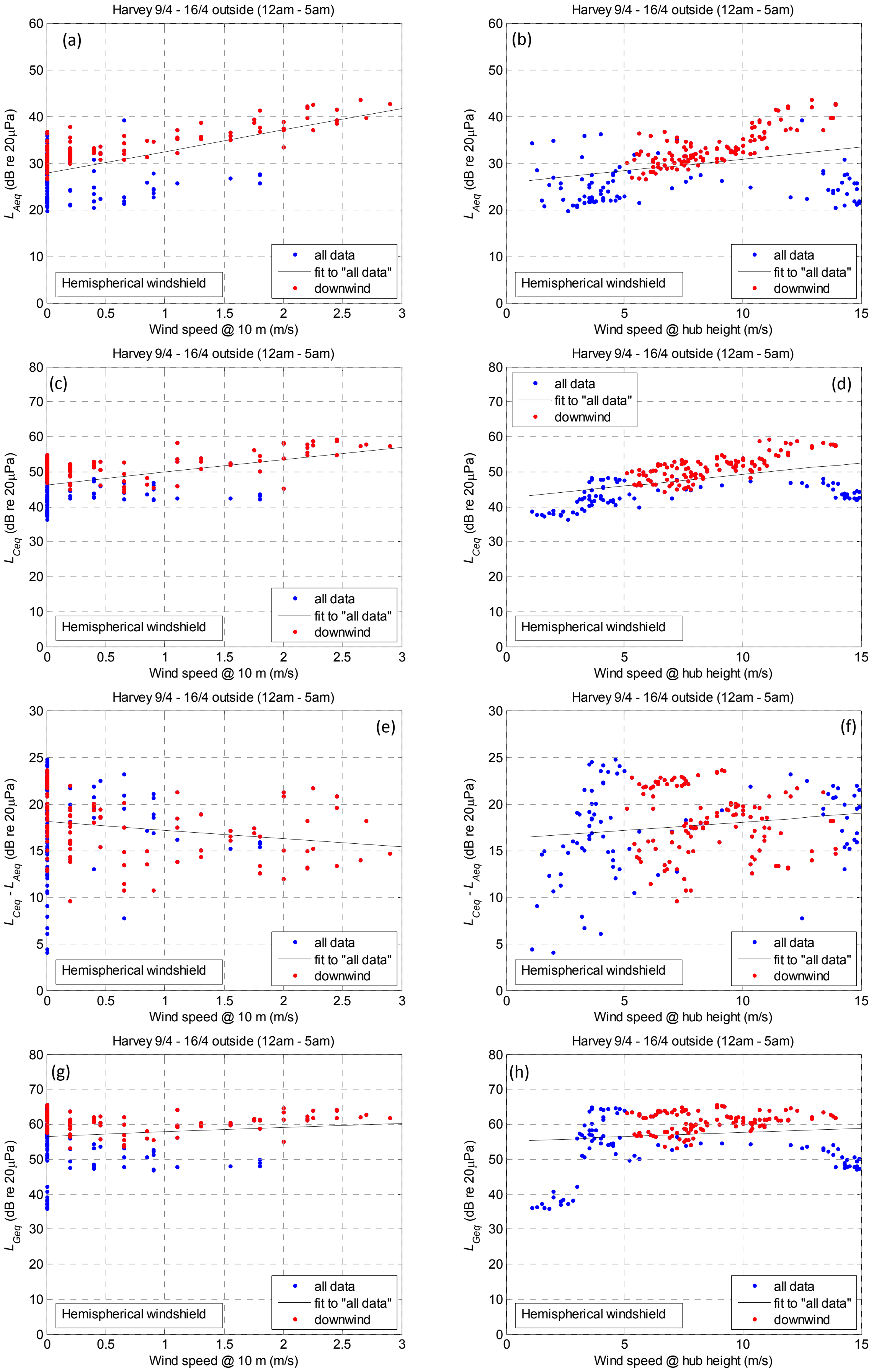


Figure 6 – Outdoor measurement results, Township 2 site.

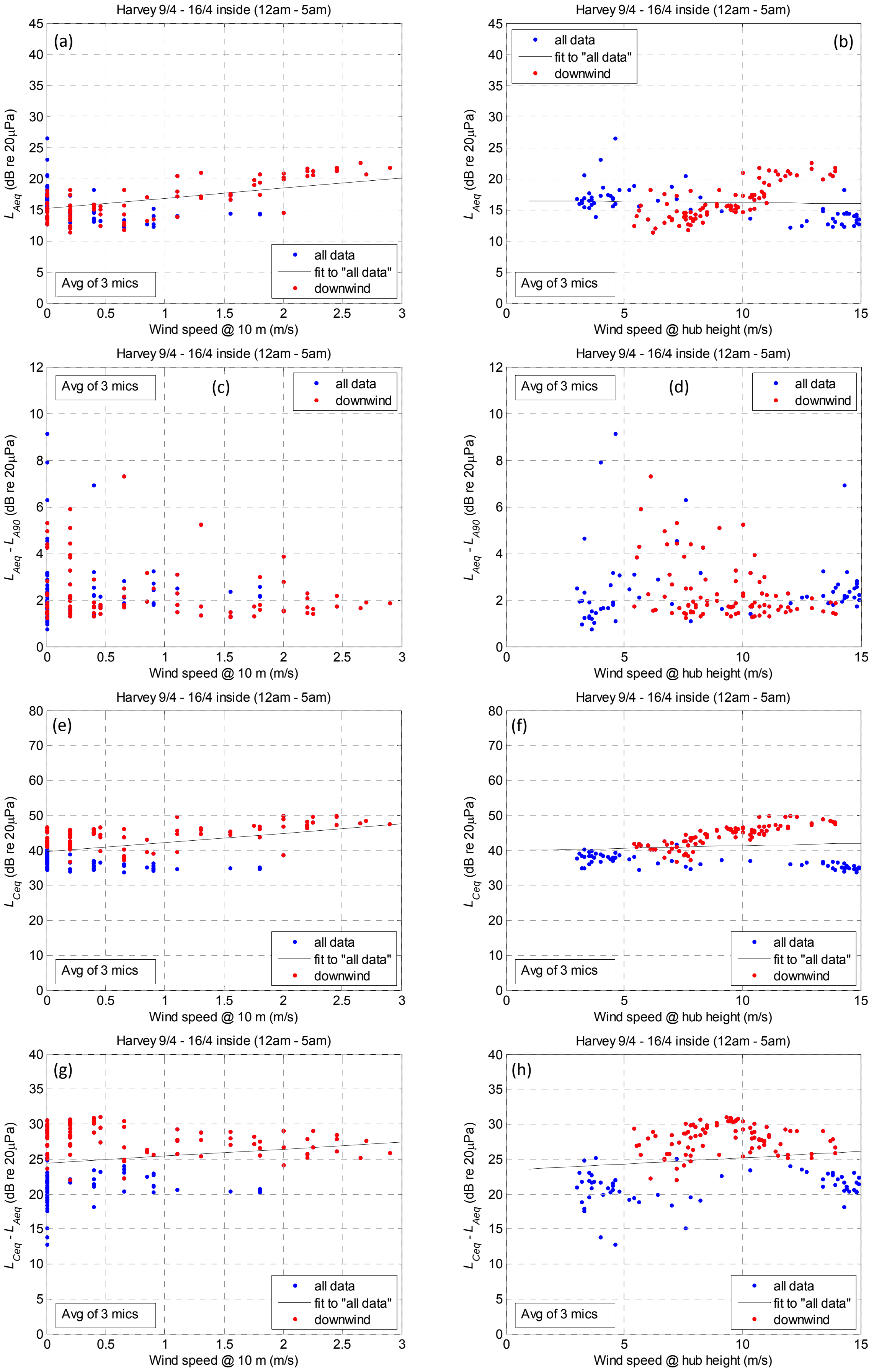


Figure 7 – Indoor measurement results, Township 2 site (first set)

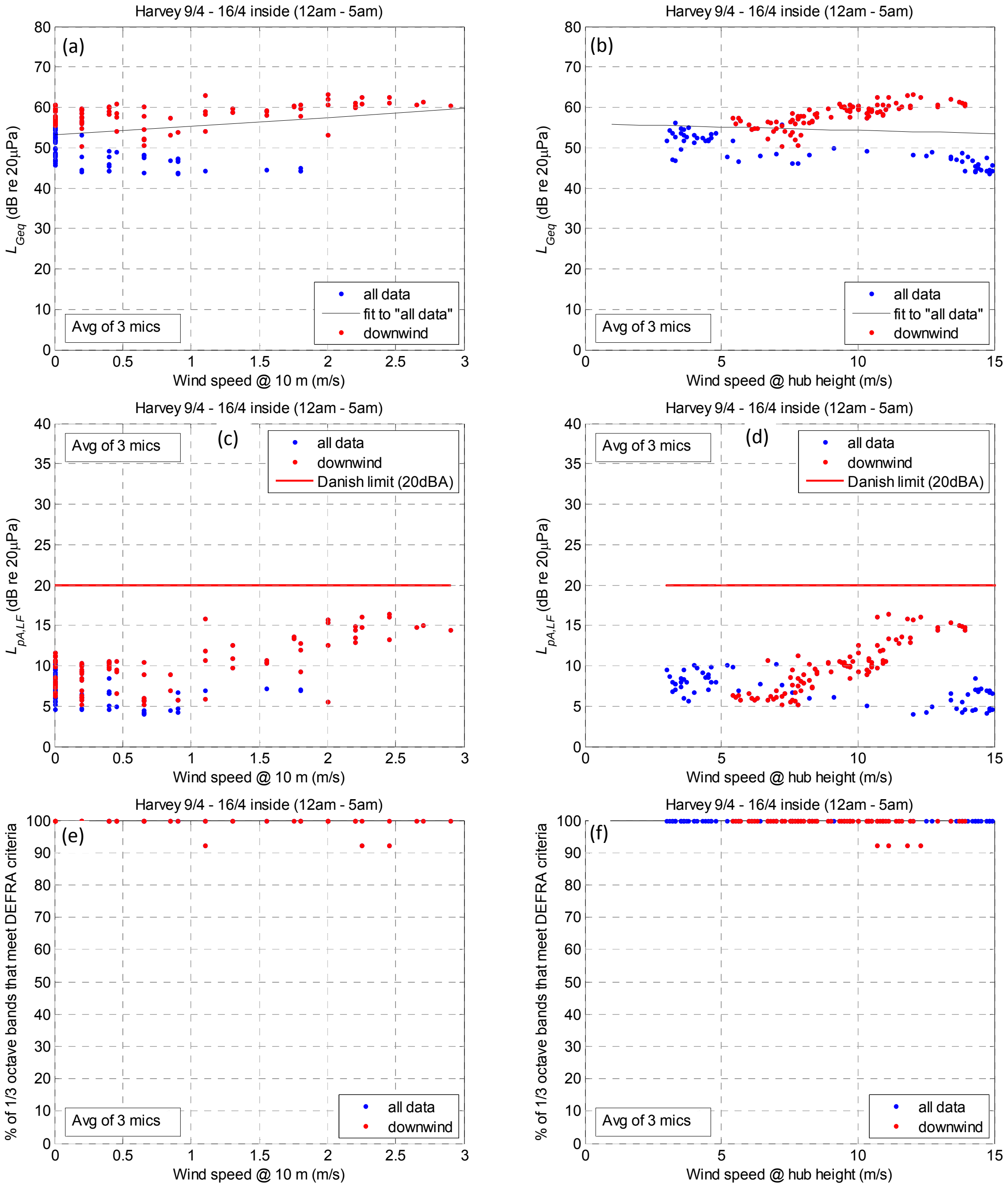
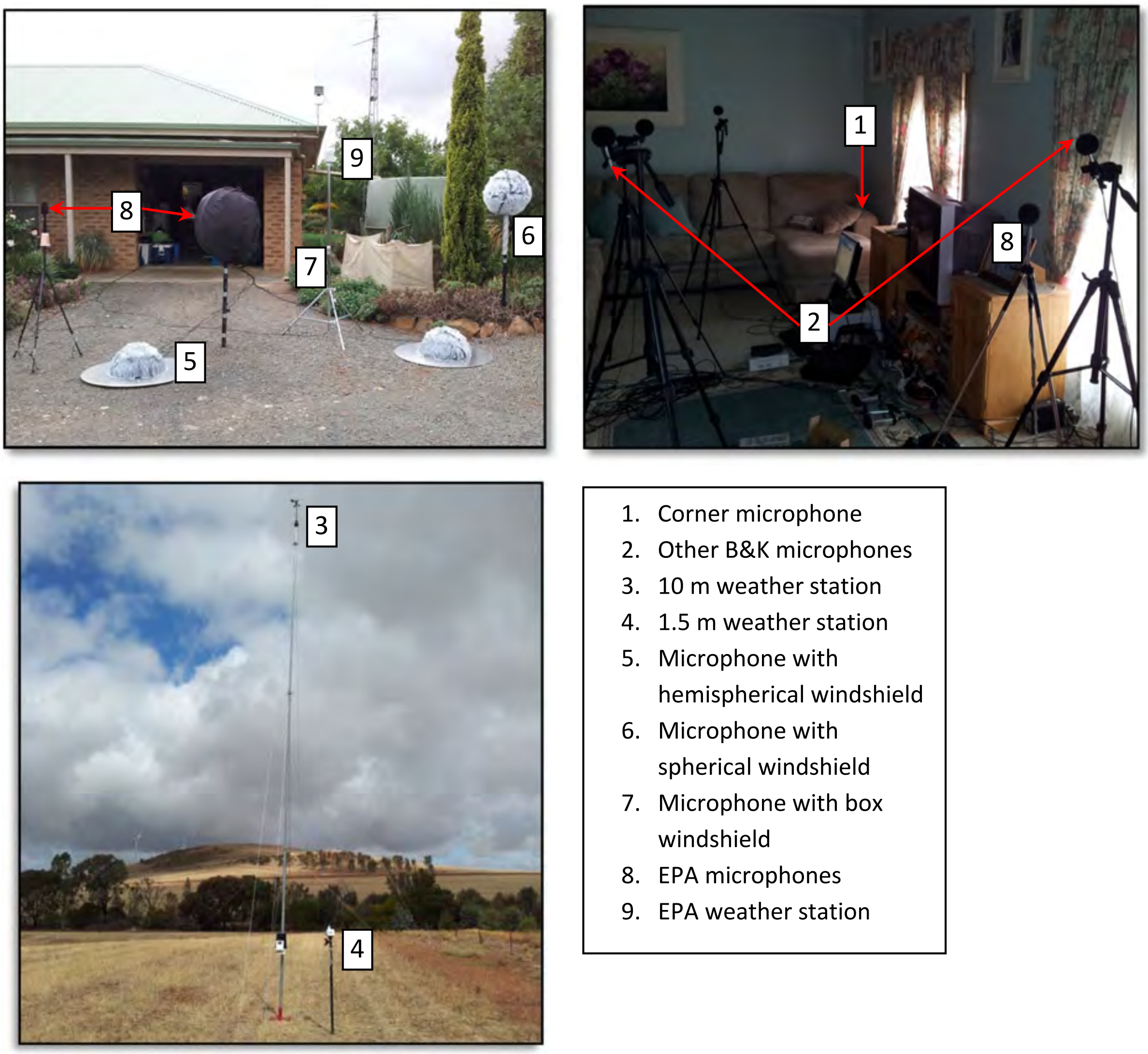


Figure 8 - Indoor measurement results, Township 2 site (second set)

4.3 North site

The residence at which the measurements were taken is the same as the one used in the EPA study. The closest wind turbine to this measurement site is ‘AG’, which is 1.3 km from the residence. The downwind direction from the closest wind turbine to the residence is between 127° and 217°. It is estimated that this residence was built in the late 1990s. The walls are constructed of brick-veneer, the windows are a medium-sized aluminium framed sash design and the roof consists of corrugated sheet steel. All internal walls and ceilings are insulated with batts and the ceiling is constructed from gyprock. The indoor instruments were located in the room closest to the wind farm, which has one window which faces perpendicular to the wind farm and a garage on the wind farm side. For the majority of the measurements, the residence was occupied and electrical appliances were operating inside in an adjacent room. One night during the measurement period, the residents stayed elsewhere. The zoning for this residence is “rural industrial”. The instrumentation set-up is shown in Figure 9.



1. Corner microphone
2. Other B&K microphones
3. 10 m weather station
4. 1.5 m weather station
5. Microphone with hemispherical windshield
6. Microphone with spherical windshield
7. Microphone with box windshield
8. EPA microphones
9. EPA weather station

Figure 9 – Instrumentation set-up at North residence.

This outdoor microphone arrangement was chosen to ensure that the instruments were in a similar position to those of the EPA. For all other measurements described in this report, the instruments were positioned further from surrounding obstacles and trees and it was decided that it was more important to measure in an open area than it was to duplicate the set-up adopted by the EPA. The microphones used for the indoor averaging are labelled 1 and 2, where the corner microphone was positioned in the room corner closest to the wind farm. The outdoor instrumentation was located as shown in Figure 9. The weather stations were positioned in an open field about 50 m from the residence to avoid shielding and eddies associated with obstacles such as the house and trees. The wind turbines are visible in the background from the open field in which the wind speed and direction measurements were taken.

The results presented in the following analysis were collected over one week from 16th April – 22nd April 2013. The outdoor results shown in Figure 10 were obtained using a single microphone mounted on a ground board and protected from the wind by a secondary hemispherical windshield. The data plotted in Figure 11 and Figure 12 show the average noise levels for the three indoor microphones pictured in Figure 9.

Considering the overall A-weighted results shown in Figure 10 (a) and (b), there are many occasions where the measured levels exceeded the outdoor criteria of 40 dB(A). In addition, the regression curve obtained by plotting the overall A-weighted results against hub height wind speed exceeds the 40 dB(A) criteria even though files with identified vehicle and animal noise sources have been removed from the results. On the other hand, the close regression fit obtained by plotting the data against the wind speed at a height of 10 m suggests that there is a correlation between the local wind speed and the A-weighted noise level. Therefore, the relatively high noise levels at this location could either be associated with the proximity of the residence to the wind farm (~1.3 km) and/or the wind-induced noise. In any case, a significant number of data points which exceeded 40 dB(A) occurred when the wind speed at hub height was above the rated speed of the wind turbines of 15 m/s (Vestas, n.d.), which shows that the power output of the wind farm, and hence the associated noise, would have been high at these measurement times.

The outdoor C-weighted results shown in Figure 10 (c) and (d) indicate that the levels are lower than 60 dB(C) and therefore, a low-frequency noise problem is not indicated by this metric. There is a reasonable spread in the data for $L_{Ceq} - L_{Aeq}$, shown in Figure 10 (e) and (f) and the regression curve has a negative slope. This indicates that the relative influence of higher frequencies increases with wind speed which suggests that the high levels of A-weighted noise at this location may be due to local wind in the nearby trees. For this measurement set, no data points show that $L_{Ceq} - L_{Aeq} > 20$ dB and thus a low-frequency noise problem is not indicated by this metric.

The G-weighted outdoor and indoor levels shown in Figure 10 (g) and (h) and Figure 12 (a) and (b), respectively, indicate that the $L_{Geq} < 71$ dB(G) for all measurements which is lower than the 85 dB(G) audible threshold (ISO 7196, 1995). This may imply that the infrasound would not be audible to a person with normal hearing. However, it does not mean that the infrasound is not detectable (Salt & Lichtenhan, 2014), especially when the crest factor (ratio of peak to rms) of the sound is considered. This is because the threshold levels were determined for single, steady tones which are very different in character to wind farm infrasound and low-frequency sound.

The regression curve fitted to the indoor A-weighted levels and shown in Figure 11 (a) and (b) indicates that on average, the indoor levels were relatively low. On the other hand, the data ranges between a minimum of 12 dB(A) and a maximum of 27 dB(A) and there are several measurement points which exceed the regression curve by 5 dB(A) or more. Thus, there is a potential for indoor noise levels to be extremely low at this location and contributions from the wind farm would be particularly noticeable under such low noise conditions.

The difference between the overall indoor A-weighted level (L_{Aeq}) and the indoor A-weighted level exceeded for 90% of the time (L_{A90}) is shown in Figure 11 (c) and (d). The average difference between these metrics was calculated to be 4 dB(A). Even between the hours of 12am and 5am, where the contribution from extraneous noise sources is expected to be minimal, this difference can be over 10 dB(A). It should be noted that all audio files which were contaminated by vehicle noise were eliminated from this analysis. Therefore, it is possible that the large difference between the L_{Aeq} and the L_{A90} is caused by wind turbine noise, which can be highly variable with time depending on the atmospheric conditions. If this were the case, using the L_{A90} to determine compliance would lead to erroneous results.

The difference between the overall C- and A-weighted levels is on average 25 dB as shown in Figure 11 (g) and (h). This is greater than that measured outdoors by a substantial amount, particularly at high wind speeds.

At this residence, the Danish low-frequency guidelines was met on all occasions as indicated in Figure 12 (c) and (d) and the DEFRA criteria were satisfied in the majority of cases as depicted in Figure 12 (e) and (f). In those cases where the DEFRA criteria were not satisfied, the hub height wind speed was greater than 13 m/s but the residence was not downwind from the wind farm. The wind speed at a height of 10 m varied between 2 m/s and 8 m/s, which suggests that some of the cases where the DEFRA criteria were not satisfied could have been attributed to wind-induced noise. On the other hand, where the wind speed at a height of 10 m was relatively low it is probable that the wind farm caused the exceedences.

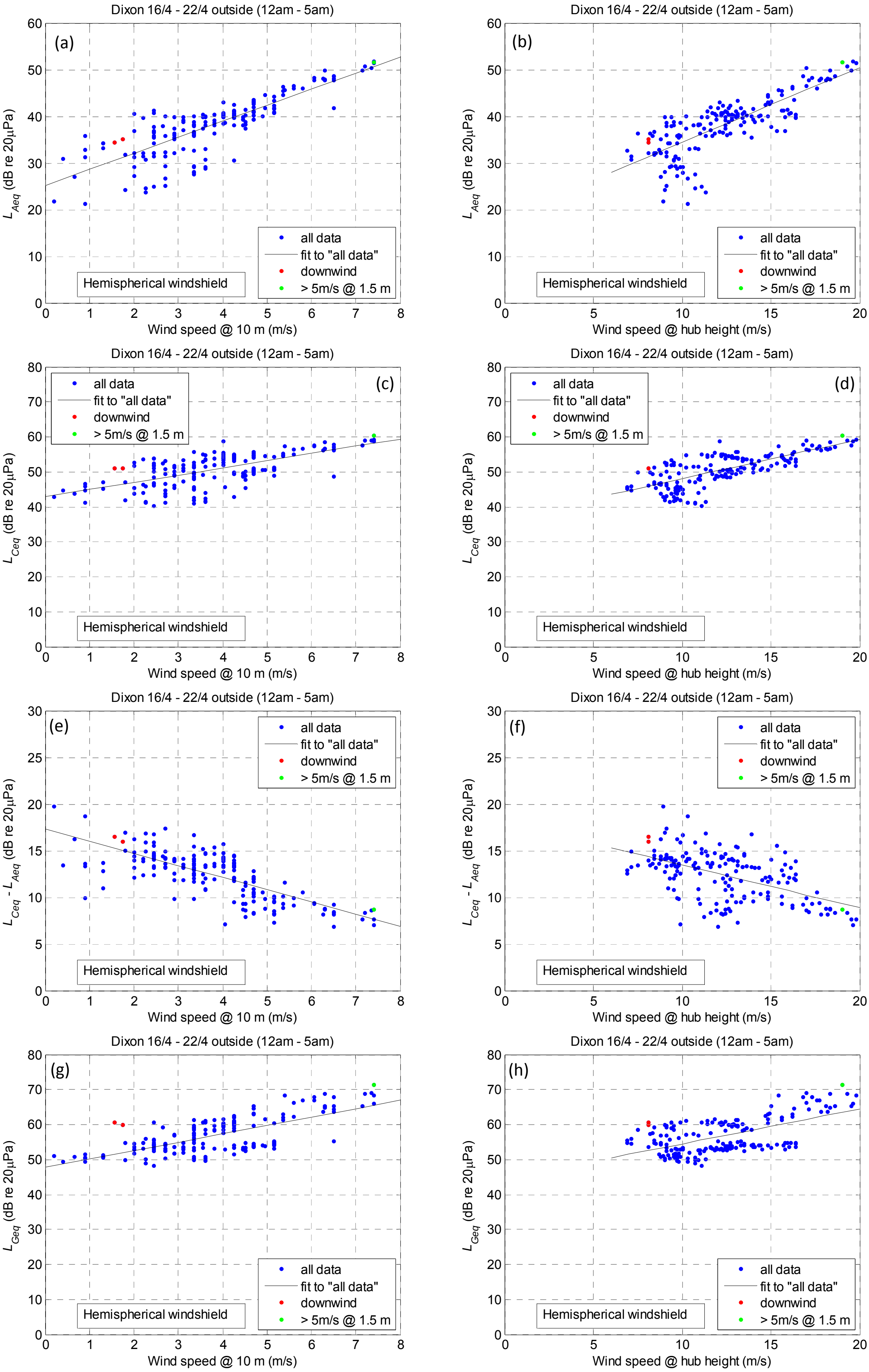


Figure 10 – Outdoor measurement results for North residence.

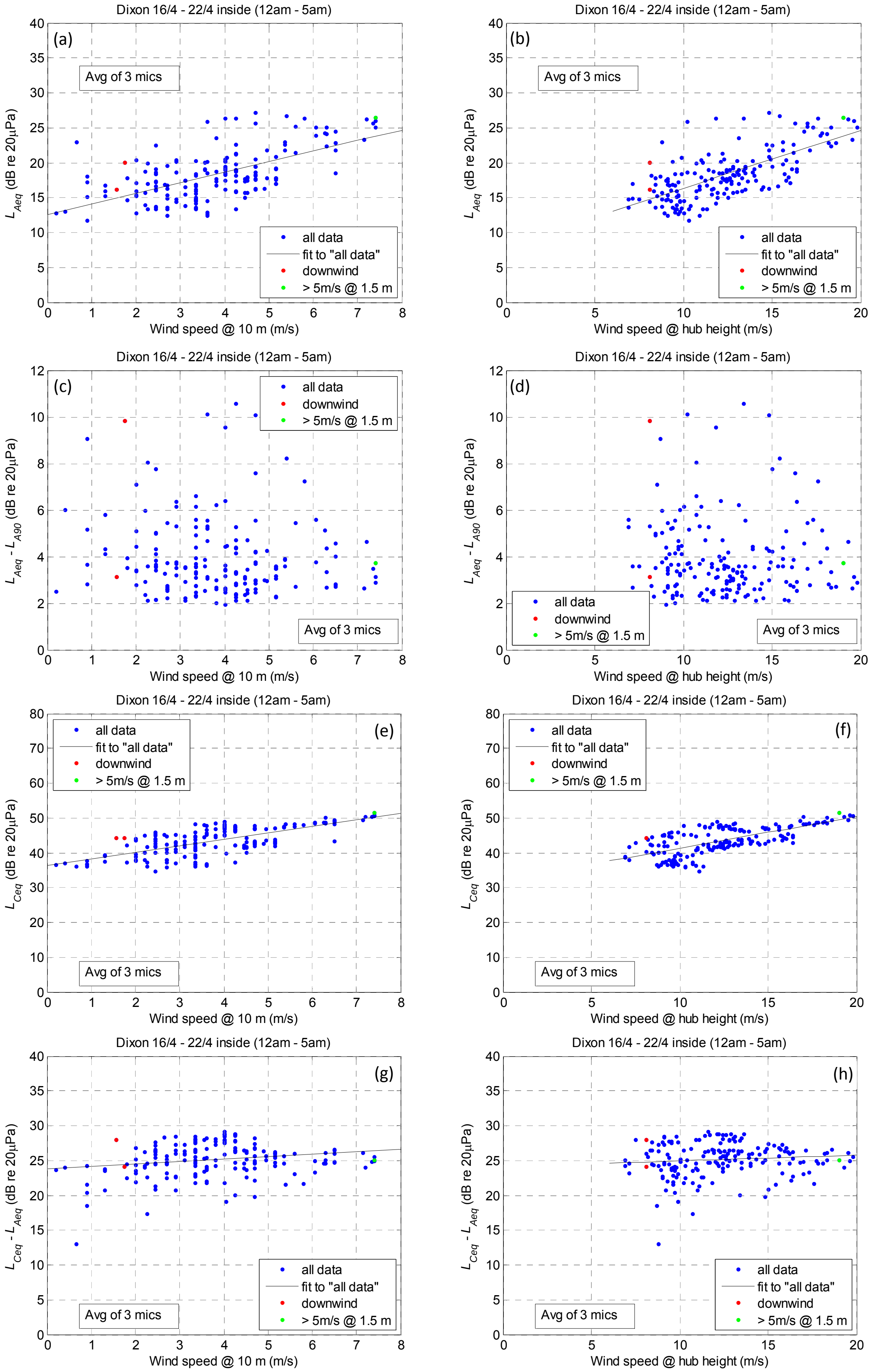


Figure 11 – Indoor measurement results for North residence (first set).

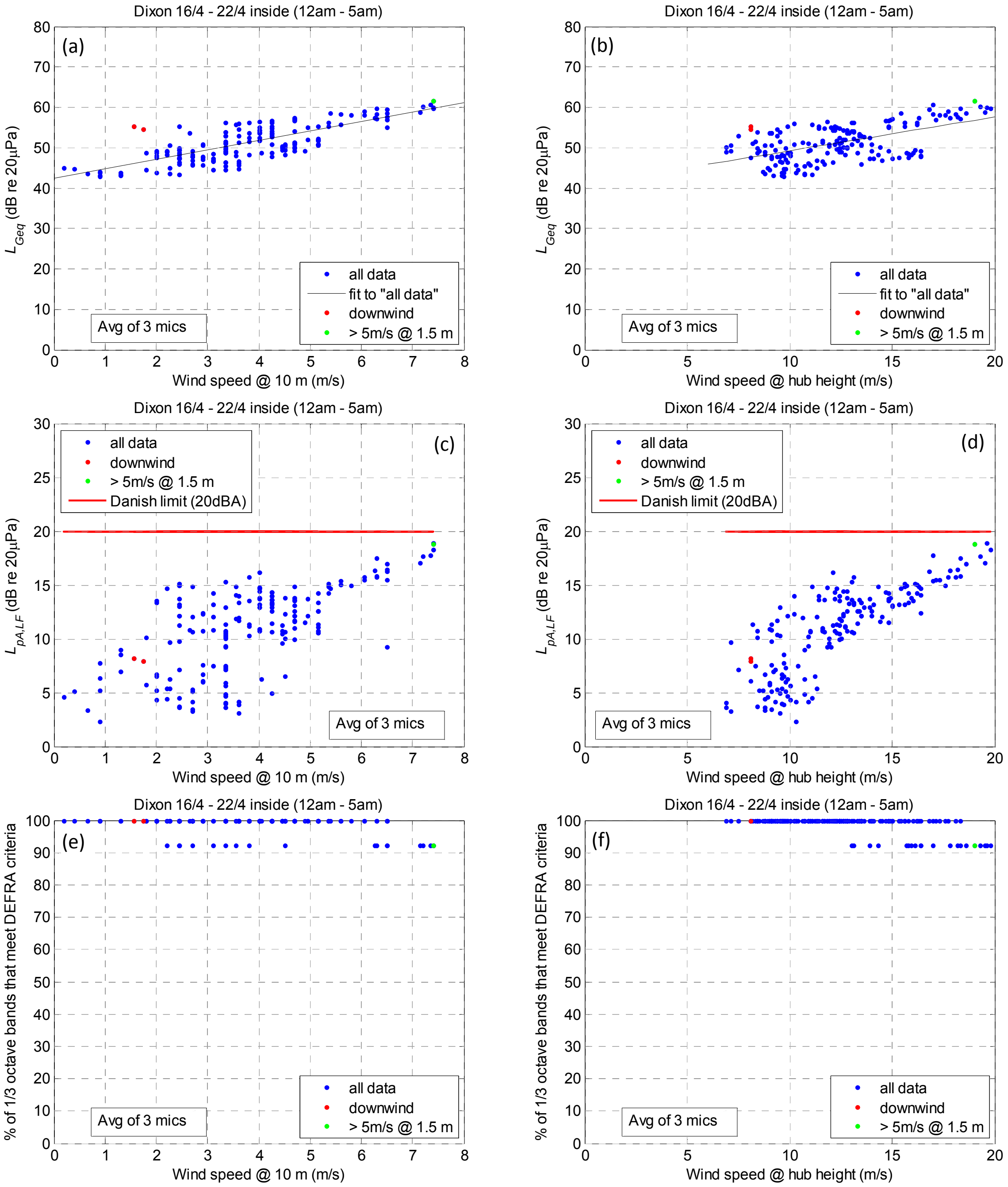
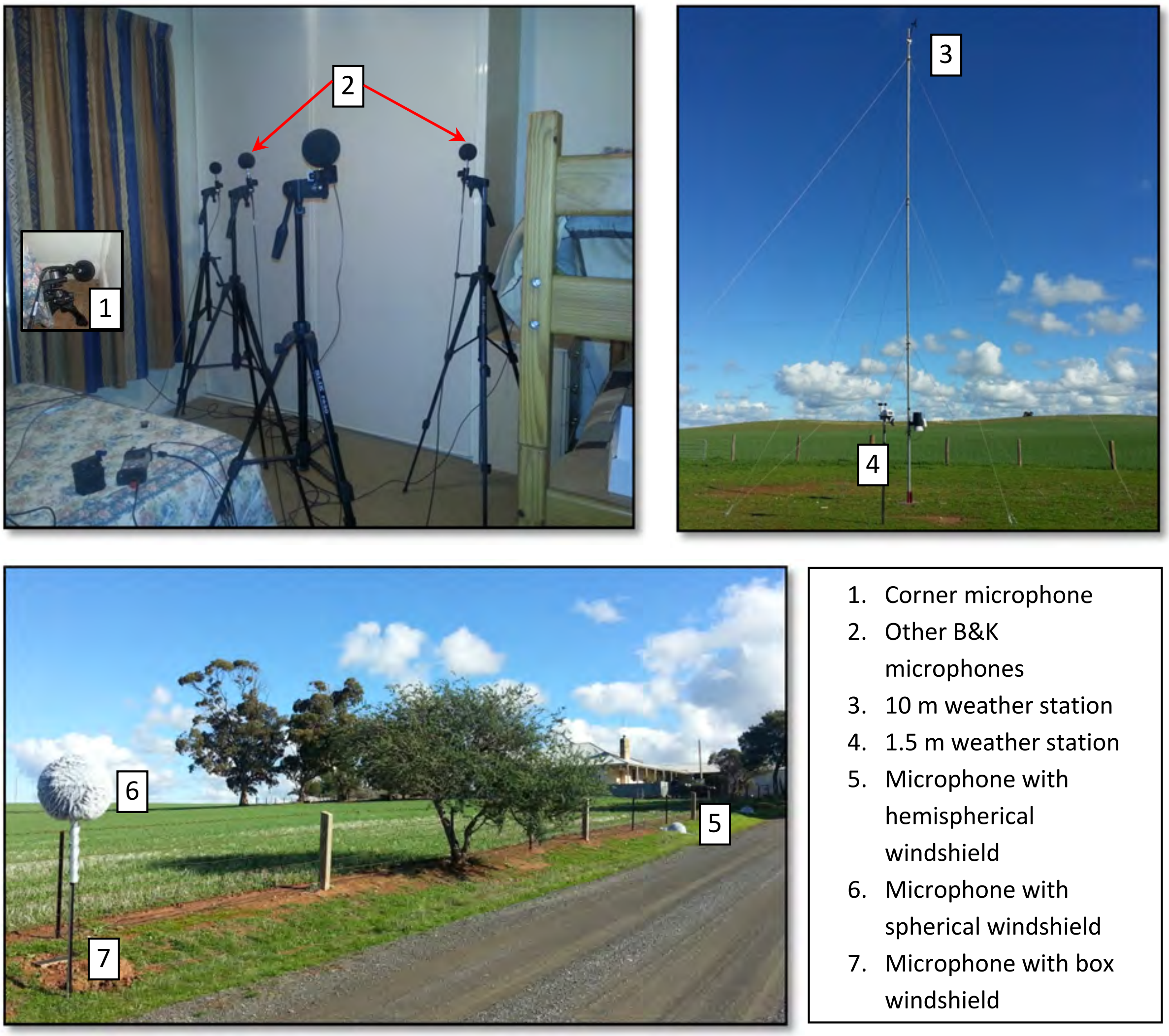


Figure 12 – Indoor measurement results for North residence (second set).

4.4 West site

The residence at which the measurements were taken is the same as the one used in the EPA study. The closest wind turbine to this measurement site is ‘BH’, which is 2.5 km from the residence. The downwind direction from the closest wind turbine to the residence is between 53° and 143°. The residence has walls which are constructed from weatherboard, large aluminium framed sliding windows and the roof consists of corrugated sheet steel. The wall thickness is 100 mm in total, where 25 mm of the thickness consists of cladding. The ceiling is constructed from plasterboard and there is no insulation in the ceiling space or walls. The indoor instrumentation was located in one of the bedrooms facing the wind farm which has a window facing the wind farm. For the majority of the measurements, the residence was unoccupied but a refrigerator was still operating in the kitchen. The zoning for this residence is “rural industrial”. The instrumentation set-up is shown in Figure 13.



1. Corner microphone
2. Other B&K microphones
3. 10 m weather station
4. 1.5 m weather station
5. Microphone with hemispherical windshield
6. Microphone with spherical windshield
7. Microphone with box windshield

Figure 13 – Instrumentation set-up at West residence.

The microphones used for the indoor averaging are labelled 1 and 2, where the corner microphone was positioned in the room corner closest to the wind farm. The outdoor instrumentation was located along the road leading to the property, as shown. It would have been preferable to locate the outdoor microphones in the paddock at the front of the house which faces the wind turbines but crops had just been planted and hence the paddock could not be used. Nevertheless, the outdoor microphones were sufficiently far from obstacles such as the house and trees which would have associated wind-induced noise and eddies.

The weather stations were located in the only open field available which was about 30 m from the residence on the opposite side to the wind farm. In this position, there was minimal interference from obstacles such as the house and trees, which would cause eddy generation. It was not possible to position the 10 m tower along the road due to the large area required to secure the guy wires.

The following results were collected over 11 days from 14th June – 24th June 2013. Due to water ingress into the microphone cables after a period of rain, the last 3 days of outdoor data were discarded. This was unfortunate as the indoor results measured during these 3 days indicated that wind farm noise was more significant during this period.

The outdoor results shown in Figure 14 were obtained using a single microphone mounted on a ground board and protected from the wind by a secondary hemispherical windshield. The data plotted in Figure 15 and Figure 16 show the average noise levels for the three indoor microphones pictured in Figure 13.

For the duration of the outdoor measurements, the wind speed at hub height was generally below 10 m/s, which is significantly lower than the rated speed of the wind turbines of 15 m/s (Vestas, n.d.). On the occasions where the wind speed at hub height was between 14 m/s and 18 m/s, the conditions were not downwind for the outdoor results as shown in Figure 14 (b). Hence, at this residence it appears that worst case conditions were not measured by the outdoor microphones due to water affecting the outdoor results for the last three days. However, the last 3 days of measurements provided downwind conditions where the wind speed at hub height was greater than 12 m/s for a number of data points as evident in Figure 15 (b). During this period, the wind speed at a height of 10 m was between 3 m/s and 6 m/s, which would not have been strong enough to cause significant wind buffeting of the house. Hence the indoor microphones recorded data for several measurement periods where the conditions were considered worst case.

The overall A-weighted results presented in Figure 14 (a) and (b), show that there were many occasions where the measured levels exceeded the outdoor criteria of 40 dB(A), particularly when the wind speed at hub height was greater than 14 m/s. The regression curve associated with the plot of the overall A-weighted results against hub height wind speed exceeds the 40 dB(A) criteria at higher wind speeds. Also, there is a better correlation between increased noise levels and higher hub height wind speeds than there is between increased noise levels and higher local wind speeds at a height of 10 m. This suggests that the wind farm has a greater influence over increases in the noise level at the residence than the wind-induced noise. This is further indicated by the relative slope of the regression curve, which is higher when the A-weighted results are plotted against the hub height wind speed compared to when they are plotted against the wind speed at a height of 10 m. Another observation is that there were several instances where the outdoor levels were lower than the instrumentation noise floor of 17 dB(A). At a wind speed of about 2.7 m/s, measured at a height of 10 m in the vicinity of the residence, the range of measured noise levels spanned 17 dB(A) to 43 dB(A). Since the ambient noise levels should not have varied significantly for measurements taken between 12 am and 5 am for a given wind speed, the increased noise levels are attributed to higher hub height wind speeds which resulted in an increase in wind farm noise generation. Hence, there are several indicators which suggest that wind farm noise contributed to increases in the overall A-weighted levels. It should be noted that measurements with A-weighted levels greater than 40 dB(A) with identified vehicle and animal noise sources have been eliminated from the results.

The outdoor C-weighted results shown in Figure 14 (c) and (d) indicate that the levels are lower than 60 dB(C) and therefore, a low-frequency noise problem is not indicated by this metric. There is a significant spread in the data for $L_{Ceq} - L_{Aeq}$, shown in Figure 10 (e) and (f) and the regression curve has a negative slope. This indicates that the relative influence of higher frequencies increases with wind speed. While this is often an indicator of noise caused by the wind, the local wind speed at a height of 10 m was relatively low and did not exceed 5 m/s for these measurements. Therefore both tree noise and noise due to buffeting of the house by the wind would be expected to be minimal and this was confirmed by listening to the relevant audio files. There are several data points where $L_{Ceq} - L_{Aeq} = 20$ dB is exceeded, implying a potential low-frequency noise issue.

The G-weighted outdoor levels shown in Figure 14 (g) and (h), indicate that the $L_{Geq} < 65$ dB(G) for all outdoor measurements which is lower than the 85 dB(G) audible threshold (ISO 7196, 1995). This may imply that the infrasound would not be audible to a person with normal hearing. However, it does not mean that the infrasound is not detectable (Salt & Lichtenhan, 2014), especially when the crest factor (ratio of peak to rms) of the sound is considered, as discussed in Section 4.1.

There was a large spread in the overall A-weighted indoor levels from 10 dB(A) to almost 35 dB(A) as indicated in Figure 15 (a) and (b). The highest noise levels were recorded when the residence was downwind from the wind farm and the wind speed at hub height was greater than 12 m/s. A similar spread in the data was observed for the indoor A-weighted results plotted against the wind speed at a height of 10 m. Several data points were in excess of 30 dB(A), which is considered to be a suitable indoor limit for wind farm hosts (SA EPA, 2009). An even lower limit would be expected to be relevant for residents who are not hosts, as is the case at this location. For similar hub height and local 10 m high wind speeds where the residence was not downwind from the wind farm, the measured indoor levels were over 20 dB(A) lower. Indoor noise levels close to 35 dB(A) are particularly high especially since the no observed health effect limit for *outdoor* noise is 30 dB(A) according to the WHO (2009).

The difference between the overall indoor A-weighted level (L_{Aeq}) and the indoor A-weighted level exceeded for 90% of the time (L_{A90}) is shown in Figure 15 (c) and (d). The average difference between these metrics was calculated to be 2 dB(A). Even between the hours of 12am and 5am, where the contribution from extraneous noise sources is expected to be minimal, this difference can be over 8 dB(A). There are also several data points greater than 4 dB(A) for downwind conditions and hub height wind speeds between 12 m/s and 16 m/s. The corresponding local wind speed at a height of 10 m varied between 3 m/s and 6 m/s and at these wind speeds, other data points for non-downwind conditions indicate that $L_{Aeq} - L_{A90}$ can be as low as 1 dB(A). This shows that large observed differences between L_{Aeq} and the L_{A90} do not appear to be related to wind-induced noise. It should be noted that all audio files which were contaminated by vehicle noise were eliminated from this analysis. Therefore, it is probable that the large difference between the L_{Aeq} and the L_{A90} is caused by wind turbine noise, which can be highly variable with time depending on the atmospheric conditions. If this were the case, using the L_{A90} to determine compliance would lead to erroneous results.

The overall C-weighted results shown in Figure 15 (f) show that for hub height wind speeds greater than 14 m/s, there is a significant difference between results measured during downwind and other wind conditions. The difference is as much as 20 dB(C). For a given local wind speed at a height of 10 m, the overall C-weighted level can also be seen to vary by as much as 20 dB(C), which indicates that this variation cannot be attributed to wind-induced noise. On the other hand, the overall C-weighted level exceeds 60 dB(C) by only a small amount. The difference between the overall C- and A-weighted levels can be up to 5 dB higher than for the outdoor difference as shown in Figure 15 (g) and (h). Differences of $L_{Ceq} - L_{Aeq} > 30$ dB, which are indicated in Figure 15 (g) and (h), signify a potential low-frequency noise issue.

For downwind conditions where the hub height wind speed > 14 m/s, there is also a significant increase in the levels of infrasound. The wind speed at a height of 10 m measured at the residence ranges from 3 m/s to 6 m/s for these measurements, which suggests that wind-induced noise could also be contributing to the higher levels of infrasound. On the other hand, the overall G-weighted levels are as high as 74 dB(G) for downwind conditions whereas for similar hub height and local 10 m high wind speeds for non-downwind conditions, the levels are up to 20 dB(G) lower.

Data are plotted against the Danish low-frequency guidelines in Figure 16 (c) and (d) and over 20 measurements of 10 minute duration exceed the 20 dB(A) limit. All of these data points were measured during downwind conditions when the wind speed at hub height was greater than 12 m/s. The corresponding local wind speed at a height of 10 m was between 3 m/s and 6 m/s and at these wind speeds, levels as low as $L_{pA,LF}$ = 8 dB(A) were recorded at other times. These results suggest that there is an indoor low-frequency noise issue at this location for specific wind conditions.

The DEFRA criteria were also not met for a number of third-octave bands as indicated in Figure 16 (c) and (d). In most cases where the DEFRA criteria were not satisfied, the residence was downwind from the wind farm and the hub height wind speed was greater than 10 m/s. The worst cases showed that only 54% of the third-octave bands from 10 Hz to 160 Hz met the DEFRA criteria. In the cases where the DEFRA criteria were not satisfied, the local wind speed at a height of 10 m ranged from just above 1 m/s to just below 6 m/s. Other data points in this wind speed range indicate that the DEFRA criteria were satisfied for all third-octave bands. This strongly suggests that wind-induced noise is not responsible for exceedences of the DEFRA criteria.

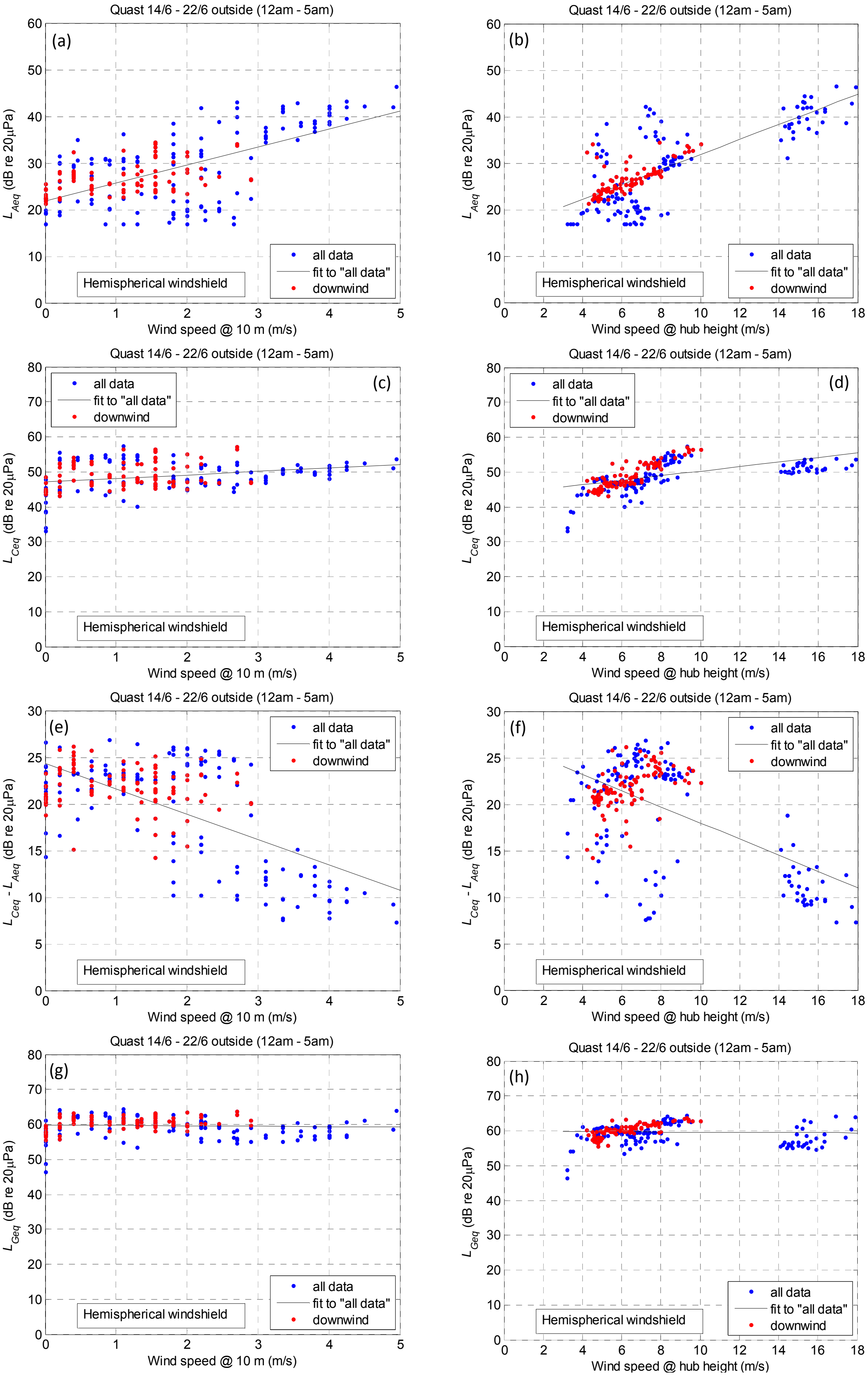


Figure 14 – Outdoor measurement results for West residence.

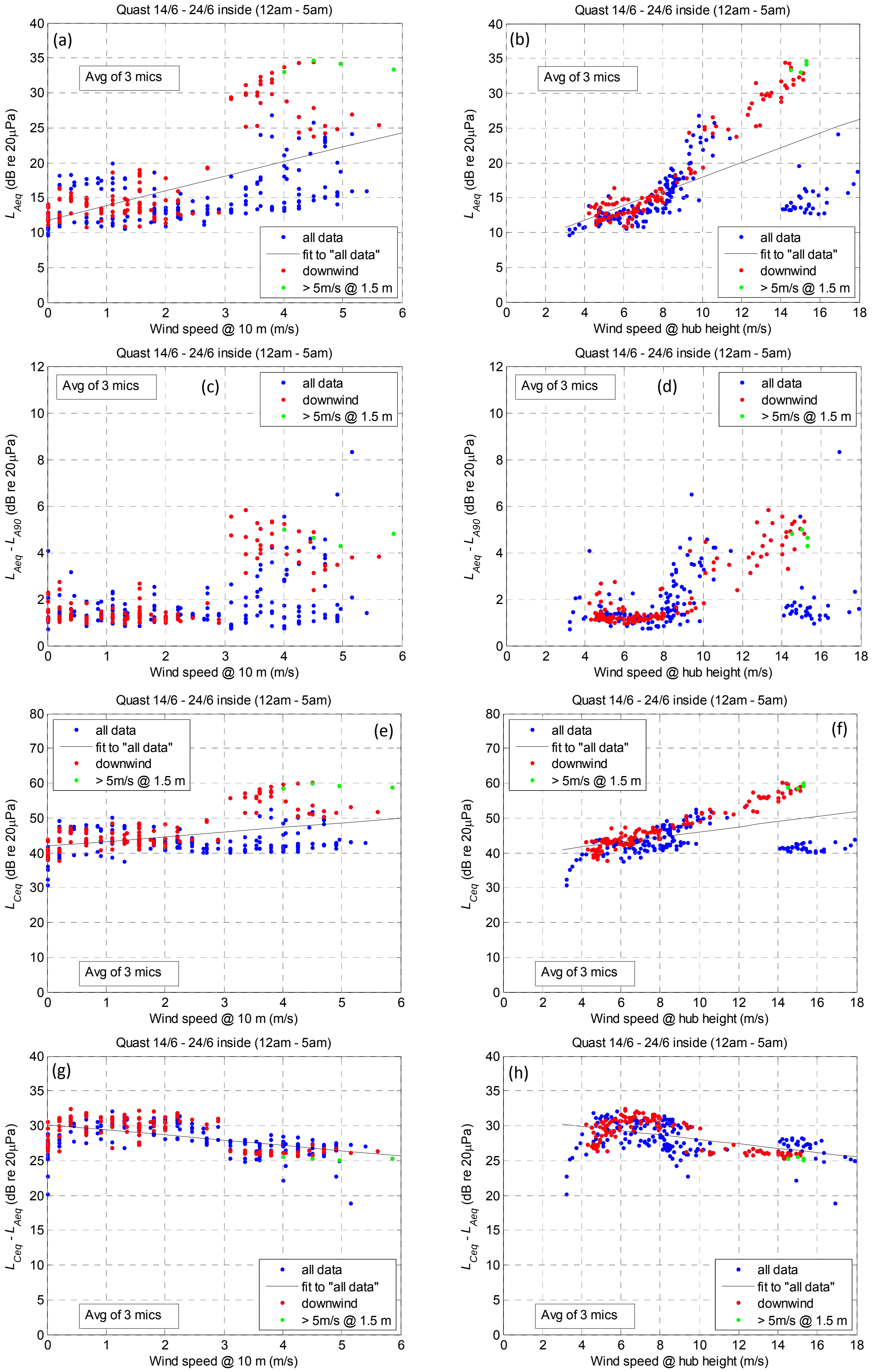


Figure 15 – Indoor measurement results for West residence (first set).

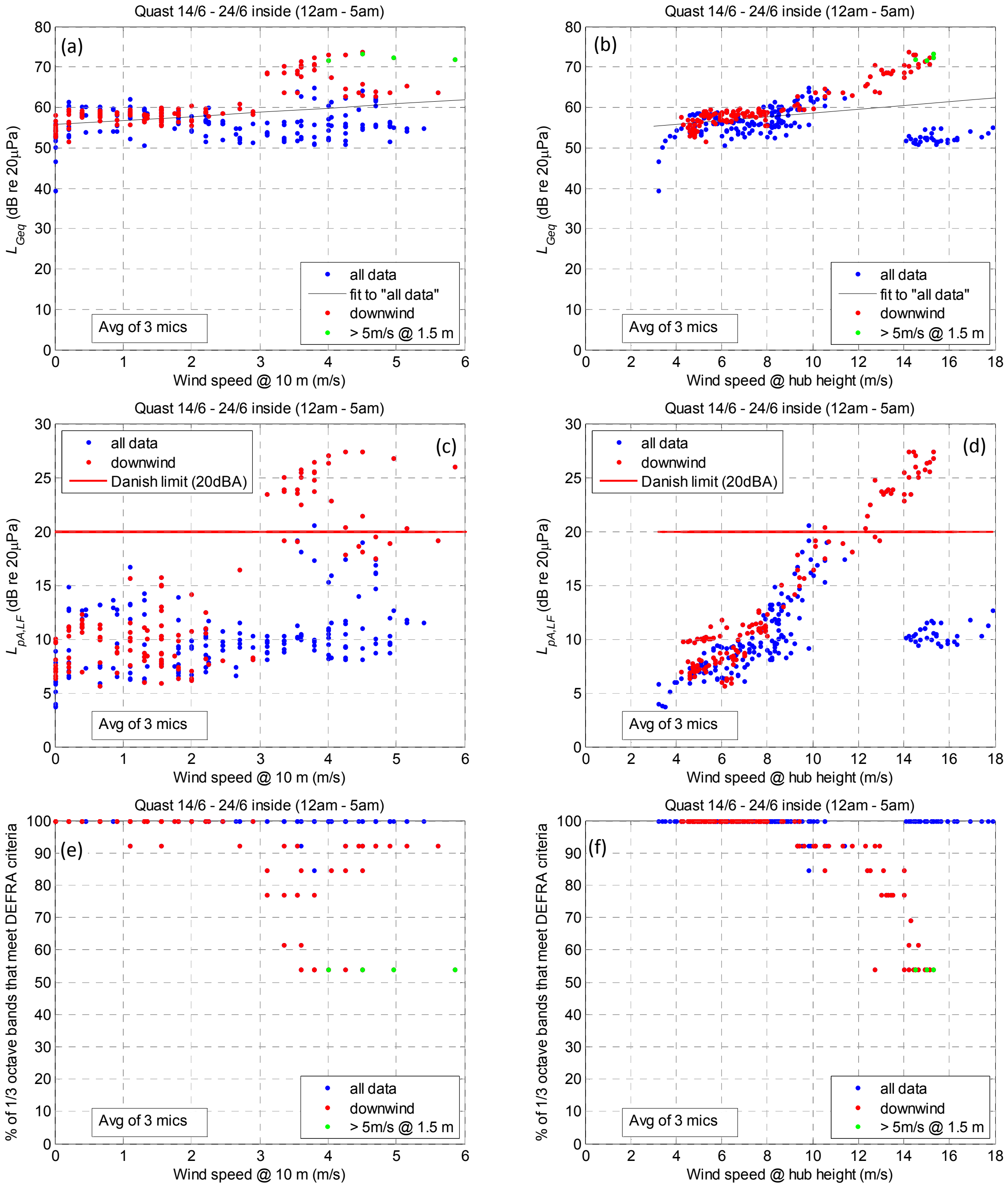


Figure 16 – Indoor measurement results for West residence (second set).

4.5 South East site

The residence at which the following measurements were taken is the same as the one used in the EPA study. The closest wind turbine to this measurement site is ‘DB’, which is 2.4 km from the residence. The downwind direction from the closest wind turbine to the residence is between 245° and 345°. It is estimated that this residence was built in the 1960s to 1980s. The walls are constructed of double brick and the windows are large, aluminium framed and sliding and the roof is tiled. The indoor instruments were located in a room on the opposite side of the house to the wind farm. This room has one window which faces perpendicular to the wind farm. For the duration of the measurements, the residence was occupied and electrical appliances were operating inside. The zoning for this residence is “rural industrial”. The instrumentation set-up for the measurements at this residence is shown in Figure 17.

1. Corner microphone
2. Other B&K microphones
3. 10 m weather station
4. 1.5 m weather station
5. Microphone with hemispherical windshield
6. Microphone with spherical windshield
7. Microphone with box windshield
8. EPA weather station

Figure 17 – Instrumentation set-up at South East residence

The microphones used for the indoor averaging are labelled 1, 2a and 2b. The indoor microphone labelled 2b is shown relative to both the door and the window. The corner microphone was positioned in the room corner closest to the wind farm. The outdoor instrumentation was located about 50 m from the residence to avoid reflective surfaces, wind-induced noise past obstacles and also to avoid shielding from the wind farm.

The results presented in the following analysis were collected over a period of 1 week from 14th May – 20th May 2013. The outdoor results shown in Figure 18 were obtained using a single microphone mounted on a ground board and protected from the wind by a secondary hemispherical windshield. The data plotted in Figure 19 and Figure 20 show the average noise levels for the three indoor microphones pictured in Figure 17.

The outdoor A-weighted data are shown in Figure 18 (a) and (b) and for the duration of the measurements, the overall A-weighted level did not exceed the 40 dB(A) criteria. On the other hand, the wind speed at hub height did not exceed 12 m/s for the measurement period as well which is well below the rated speed of the wind turbines of 15 m/s (Vestas, n.d.). Also, the local wind speed at a height of 10 m was less than 3 m/s for the duration of the measurements. The best regression fit is obtained for the overall A-weighted results plotted against hub height wind speed for this location.

The outdoor C-weighted results shown in Figure 18 (c) and (d) indicate the L_{Ceq} exceeds the 60 dB(C) level by only a small amount and thus a low-frequency noise issue is not indicated by this metric. On the other hand, the difference between the overall outdoor A-weighted and C-weighted levels shown in Figure 18 (e) and (f) reveals that there may in fact be a low-frequency noise problem. There is a large spread in the data but generally, $L_{Ceq} – L_{Aeq}$ increases with wind speed.

The G-weighted outdoor levels shown in Figure 18 (g) and (h) and Figure 20 (a) and (b) indicate that the L_{Geq} is less than 66 dB(G) for all measurements, which is well below the publicised threshold of 85 dB(G) (ISO 7196, 1995). This may imply that the infrasound would not be audible to a person with normal hearing. However, it does not mean that the infrasound is not detectable (Salt & Lichtenhan, 2014), especially when the crest factor (ratio of peak to rms) of the sound is considered, as discussed in Section 4.1.

The A-weighted levels measured indoors are shown in Figure 19 (a) and (b). The measured levels of indoor noise are as low as 7 dB(A), which shows that in some instances, there is very little masking noise. On other occasions, the indoor noise levels are close to 30 dB(A), but there is little correlation between increased hub height wind speeds and increased indoor levels. There is also minimal correlation between increased indoor noise levels and the local 10 m-high wind speed. This implies that the high indoor levels are probably not related to increased noise levels from the wind farm or wind-induced noise.

The difference between the overall indoor A-weighted level (L_{Aeq}) and the indoor A-weighted level exceeded for 90% of the time (L_{A90}) is shown in Figure 19 (c) and (d). The average difference between these metrics was calculated to be 3.7 dB(A). Even between the hours of 12am and 5am, where the contribution from extraneous noise sources is expected to be minimal, this difference can be greater than 10 dB(A). It should be noted that all audio files which were contaminated by vehicle noise were eliminated from this analysis. Therefore, it is probable that the large difference between the L_{Aeq} and the L_{A90} is caused by wind turbine noise, which can be highly variable with time depending on the atmospheric conditions. If this were the case, using the L_{A90} to determine compliance would lead to erroneous results.

There is a large amount of scatter in the data for the indoor L_{Ceq} - L_{Aeq} shown in Figure 19 (g) and (h). On average, the indoor results are about 5 dB higher than the corresponding outdoor results shown in Figure 18 (e) and (f). Numerous data points exceed the difference of L_{Ceq} - L_{Aeq} = 20 dB by a large amount, which reflects the larger bias towards noise at lower frequencies which occurs indoors, indicating that there is a low-frequency noise problem by this metric. It is well known that noise weighted to lower frequencies would be more annoying than a well-balanced spectrum (Blazier, 1997).

The Danish guideline limit of 20 dB(A) is marginally exceeded on a number of occasions as indicated in Figure 20 (c-d). In each case, the residence is downwind from the wind farm an in general, the wind speed at hub height is greater than 10 m/s. The DEFRA criteria are also not met for several measurements, as shown in Figure 20 (e-f). In these cases, only 84 - 92% of third octave bands show acceptable levels and this occurs mainly for downwind conditions when the hub height wind speed is greater than 10 m/s. For the entire measurement period, the local wind speed at a height of 10 m did not exceed 3 m/s and the wind speed at a height of 1.5 m was less than 1.6 m/s. Such low wind speeds could not have led to generation of sufficient wind-induced noise to be responsible for exceedences of the Danish guidelines or DEFRA criteria. Hence, it is implied that the low-frequency noise generated by the wind farm leads to the breach of both the Danish guidelines and the DEFRA criteria. It is unfortunate that hub height wind speeds close to the rated speed of the wind turbines of 15 m/s (Vestas, n.d.) did not occur during the period in which the data were recorded.

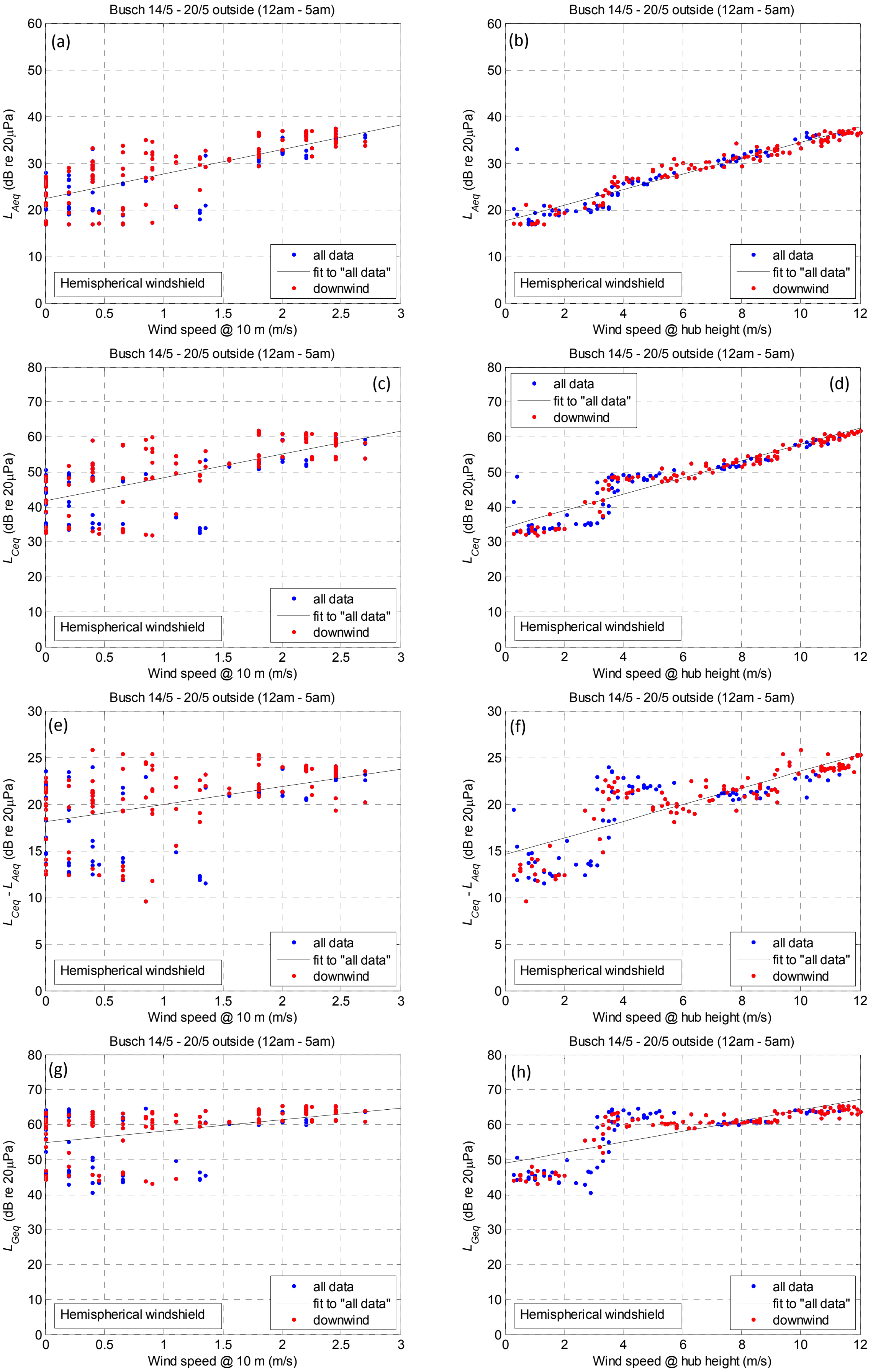


Figure 18 – Outdoor measurement results for South East residence.

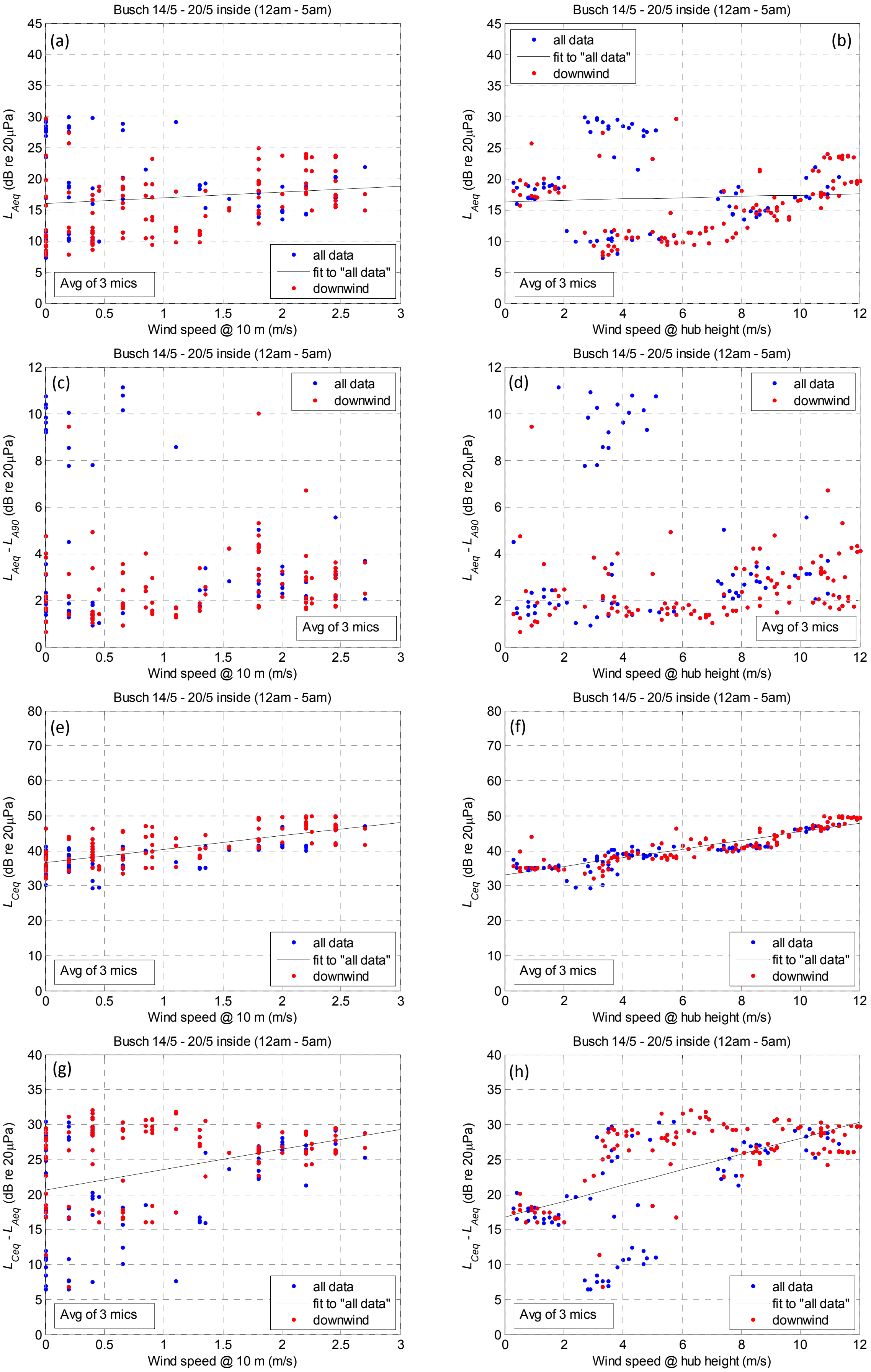


Figure 19 – Indoor measurement results for South East residence (first set).

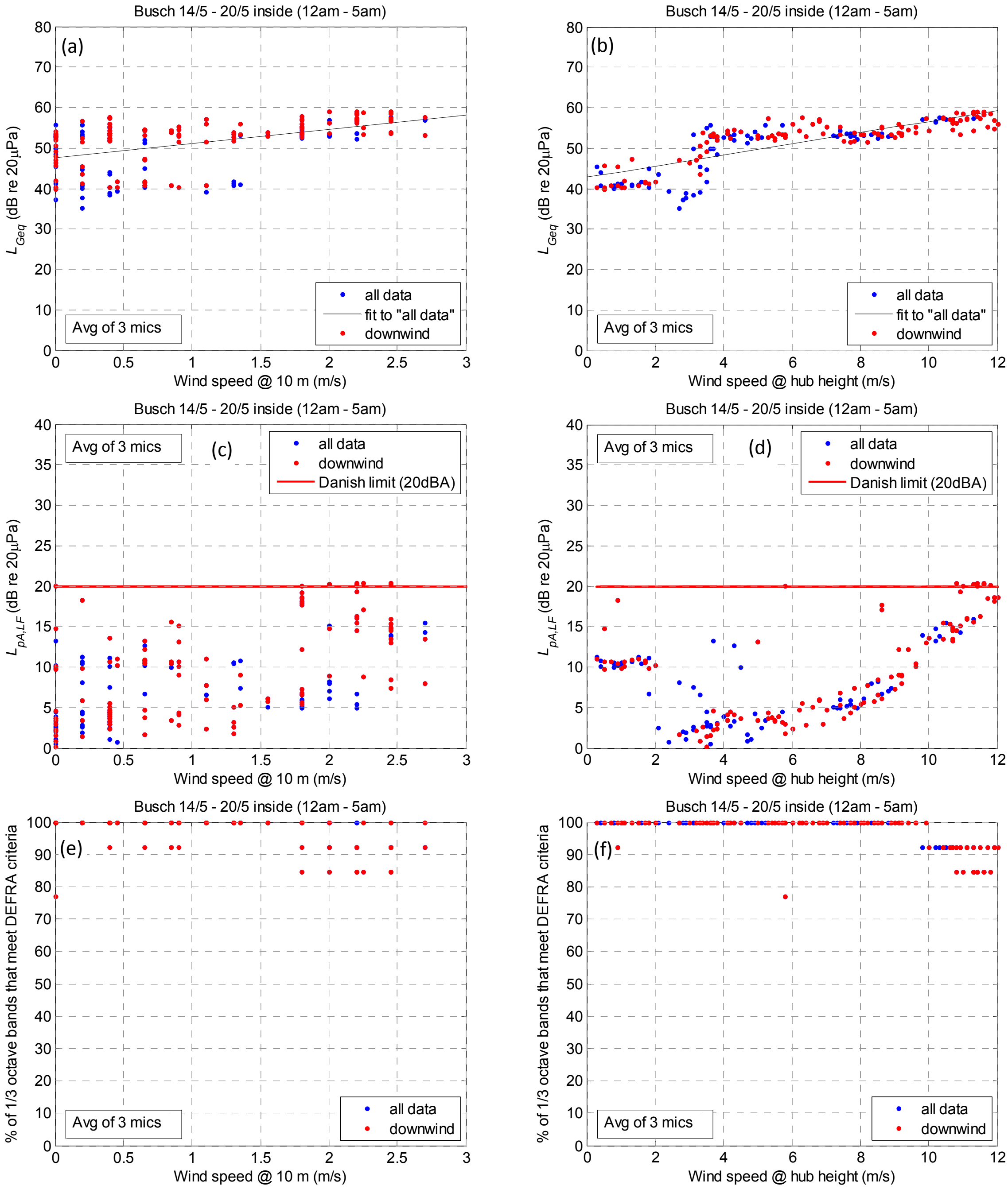
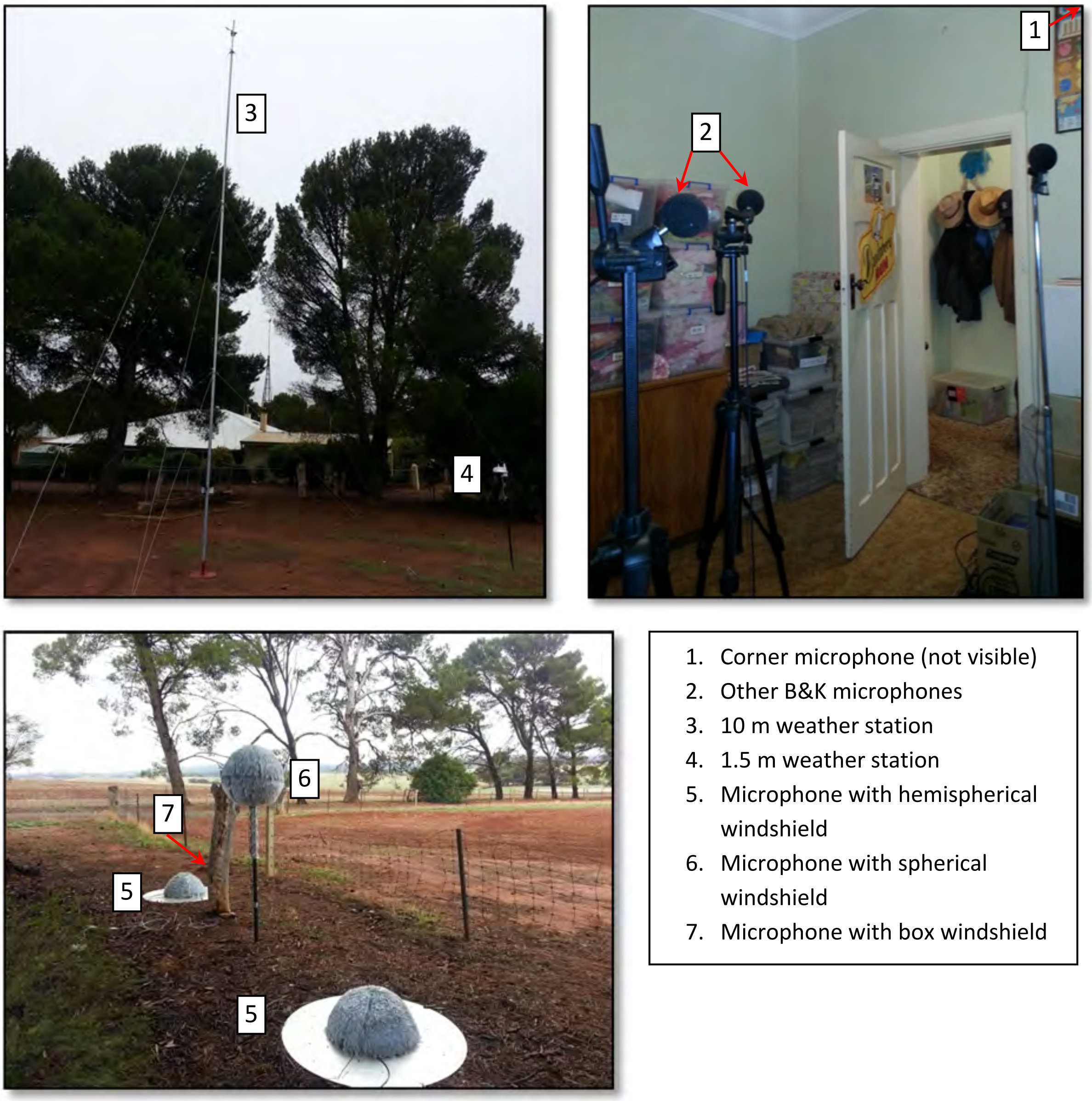


Figure 20 – Indoor measurement results for South East residence (second set).

4.6 East site

The residence at which the measurements were taken is the same as the one used in the EPA study. The closest wind turbine to this measurement site is ‘BF’, which is 7.6 km from the residence. The downwind direction from the closest wind turbine to the residence is between 223° and 313°. The walls of this residence are constructed from 320 mm thick stone and the roof consists of corrugated sheet steel. The ceiling material is plasterboard which has “Cool and Cosy” shredded paper insulation. The indoor instruments were located in the room closest to the wind farm, which has one window facing the wind farm. For the majority of the measurements, the residence was occupied and electrical appliances were operating. These appliances were located in the kitchen and laundry, at the other end of the house. The zoning for this residence is “rural industrial.” The instrumentation set-up is shown in Figure 21.



1. Corner microphone (not visible)
2. Other B&K microphones
3. 10 m weather station
4. 1.5 m weather station
5. Microphone with hemispherical windshield
6. Microphone with spherical windshield
7. Microphone with box windshield

Figure 21 – Instrumentation set-up at East residence.

The microphones used for the indoor averaging are labelled 1 and 2, where the corner microphone was positioned in the upper room corner closest to the wind farm. The outdoor microphones were positioned as far as possible from the nearest trees and bushes, about 20 m from the house. The weather stations were positioned in an open field, to avoid shielding, wind-induced noise and eddies associated with obstacles such as the house and trees.

The results presented in the following analysis were collected over one week from 23th April – 30th April 2013. The outdoor results shown in Figure 22 were obtained using a single microphone mounted on a ground board and protected from the wind by a secondary hemispherical windshield. The data plotted in Figure 23 and Figure 24 show the average noise levels for the three indoor microphones pictured in Figure 21.

The overall A-weighted results shown in Figure 22 (a) and (b), indicate that the noise levels were lower than the instrumentation noise floor of 17 dB(A) on a number of occasions. On the other hand, there were also several instances where the noise levels were in excess of 40 dB(A). For hub height wind speeds close to the rated speed of the wind turbines of 15 m/s (Vestas, n.d.) the noise levels even exceeded 50 dB(A) on some occasions. Many of the measurements which exceeded 40 dB(A) were associated with relatively low local wind speeds less than 4 m/s at a height of 10 m. The regression curve fitted to the A-weighted data plotted against the wind speed at hub height exceeds the 40 dB(A) criteria. All data points over 40 dB(A) with identified vehicle and animal noise sources have been eliminated from the results and thus it is reasonable to assume that the increased levels can be attributed to the wind farm.

The outdoor C-weighted results shown in Figure 22 (c) and (d) indicate that the levels are only slightly higher than 60 dB(C) and therefore, a low-frequency noise problem is not indicated by this metric. There is a reasonable spread in the data for $L_{Ceq} – L_{Aeq}$, shown in Figure 22 (e) and (f) and the regression curve has a negative slope. This indicates that the relative influence of higher frequencies increases with wind speed which shows that wind-induced noise affected some of the measurements. This is not surprising as the wind speed at a height of 1.5 m was greater than 5 m/s for a number of measurements where $L_{Ceq} – L_{Aeq}$ was relatively low. On the other hand, a large number of data points show that $L_{Ceq} – L_{Aeq} > 20$ dB when there was zero wind at the residence at a height of 10 m, thus indicating a low-frequency noise issue not associated with wind-induced noise.

The G-weighted outdoor and indoor levels shown in Figure 22 (g) and (h) and Figure 24 (a) and (b), respectively, indicate that the $L_{Geq} < 71$ dB(G) for all measurements which is lower than the 85 dB(G) audible threshold (ISO 7196, 1995). This may imply that the infrasound would not be audible to a person with normal hearing. However, it does not mean that the infrasound is not detectable (Salt & Lichtenhan, 2014), especially when the crest factor (ratio of peak to rms) of the sound is considered, as discussed in Section 4.1.

There is a large spread in the indoor A-weighted data which is shown in Figure 23 (a) and (b). The levels range from a minimum of 7 dB(A) to a maximum of about 27 dB(A), ignoring the data where the local wind speed at a height of 1.5 m was greater than 5 m/s. Given that the minimum indoor A-weighted levels are so low at this location, contributions from the wind farm would be particularly noticeable even at low levels.

A number of data points indicate larger differences between the overall indoor C- and A-weighted levels than 20 dB as shown in Figure 23 (g) and (h). For this residence, the value of this parameter is similar outdoors to indoors. The reason why the large differences occur is that there is a large amount of energy in the third-octave bands of 50 Hz and below. Since the C-weighting applies minimal weighting to these third-octave bands and the A-weighting applies a penalty between -30 dB and -70 dB, this leads to large values of the overall C minus A-weighted levels.

The Danish low-frequency guidelines was met on all occasions at this residence as indicated in Figure 12 (c) and (d) and the DEFRA criteria were also satisfied in all cases as depicted in Figure 24 (e) and (f). On the other hand, the unweighted spectra associated with the measurements where the difference between the overall indoor C- and A-weighted was greater than 20 dB show distinct peaks in the spectra, particularly in the 20 Hz, 25 Hz, 31.5 Hz and 50 Hz third-octave bands. While the low-frequency content is not high enough to exceed the Danish low-frequency guidelines and DEFRA criteria, the spectral peaks are still indicative of wind turbine noise as will be shown in Section 5.

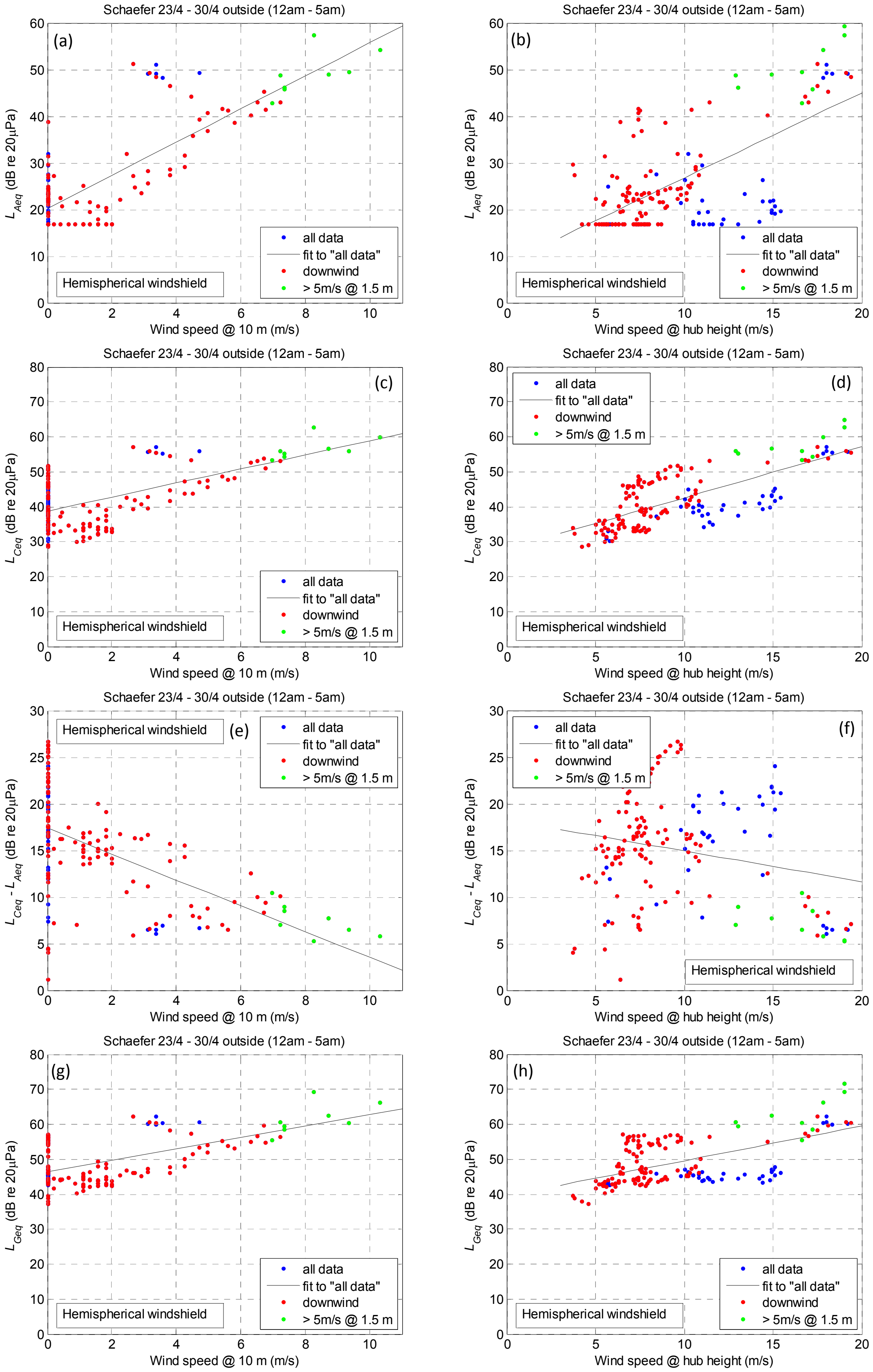


Figure 22 – Outdoor measurement results for East residence.

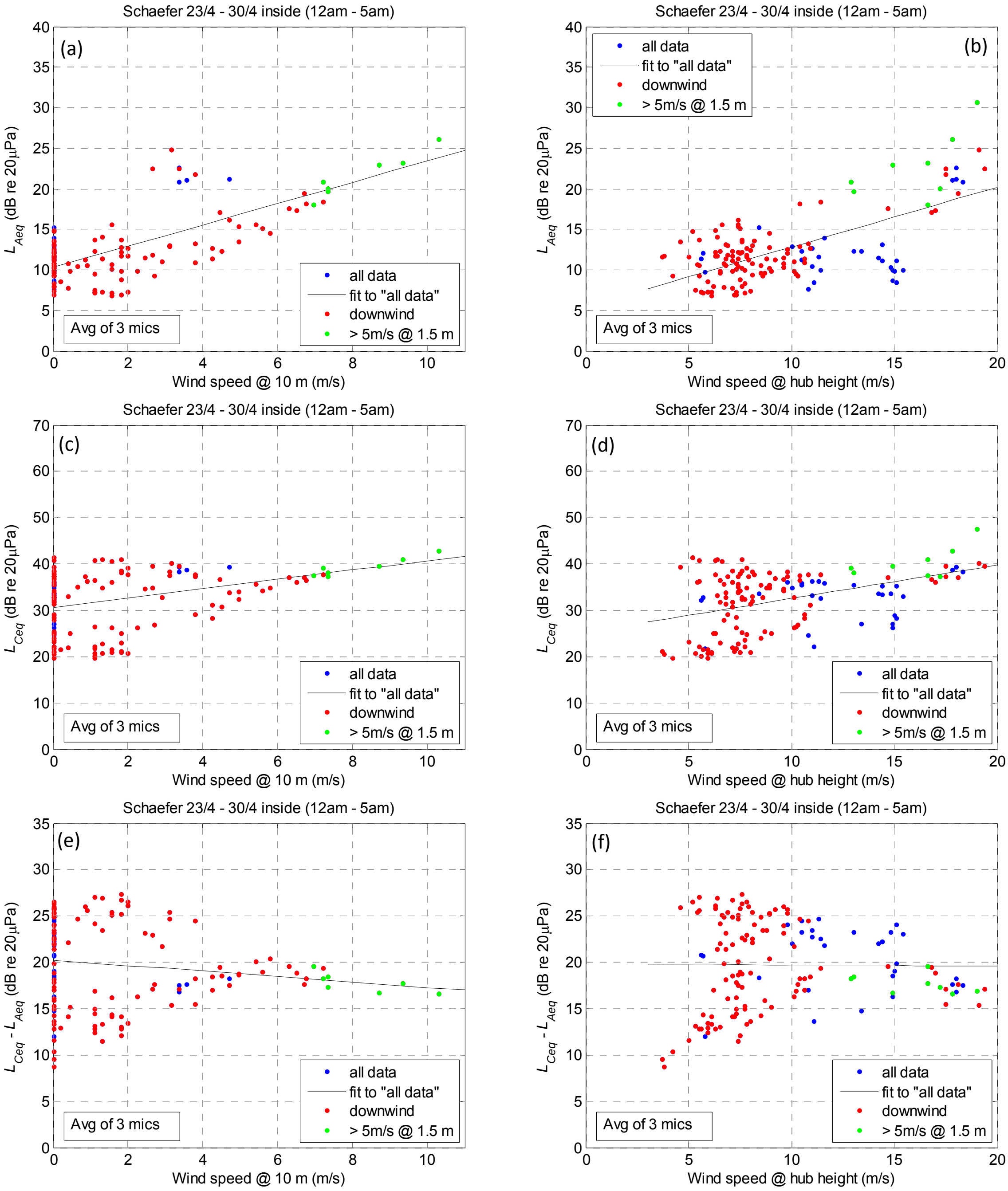


Figure 23 – Indoor measurement results for East residence (first set).

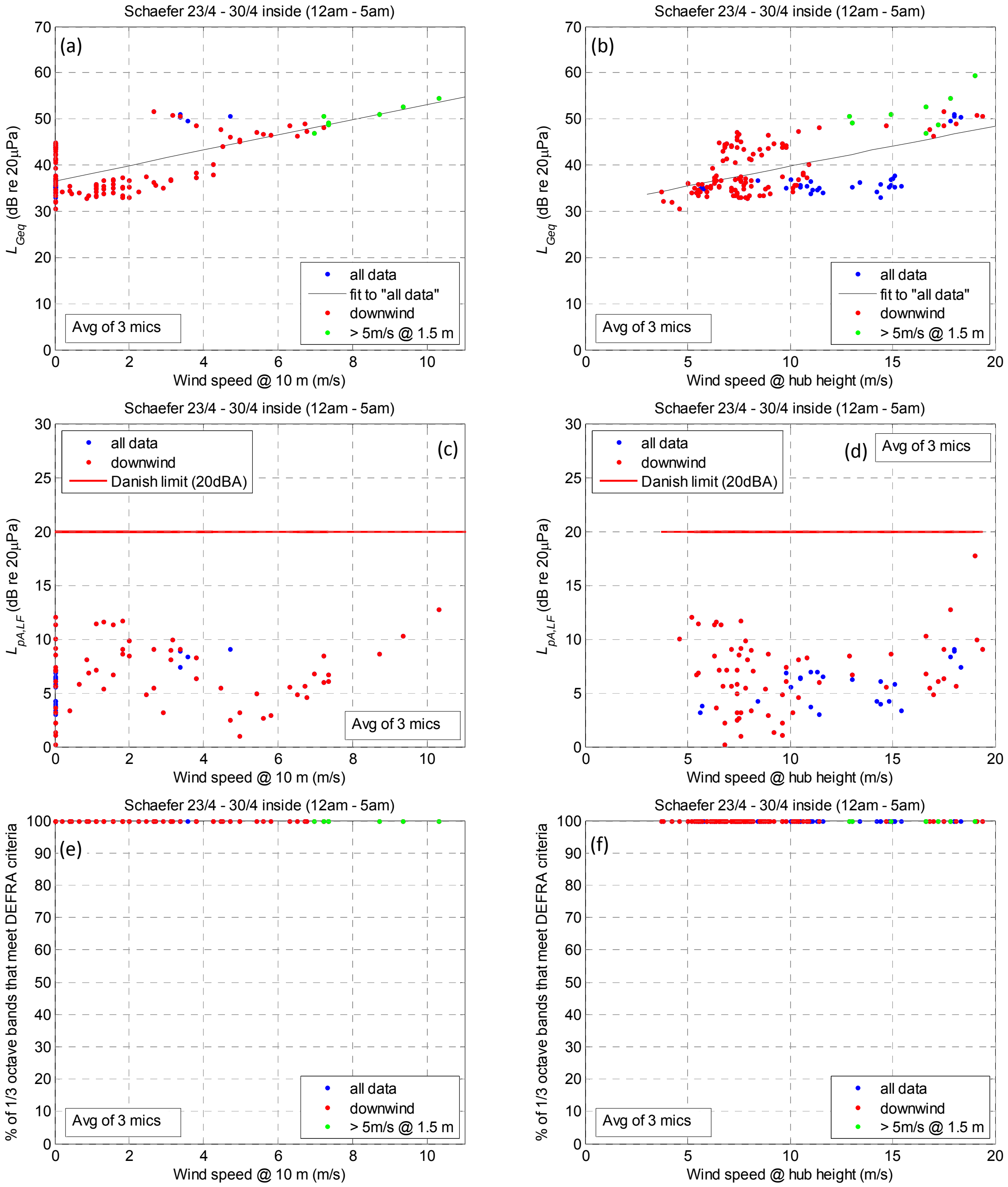
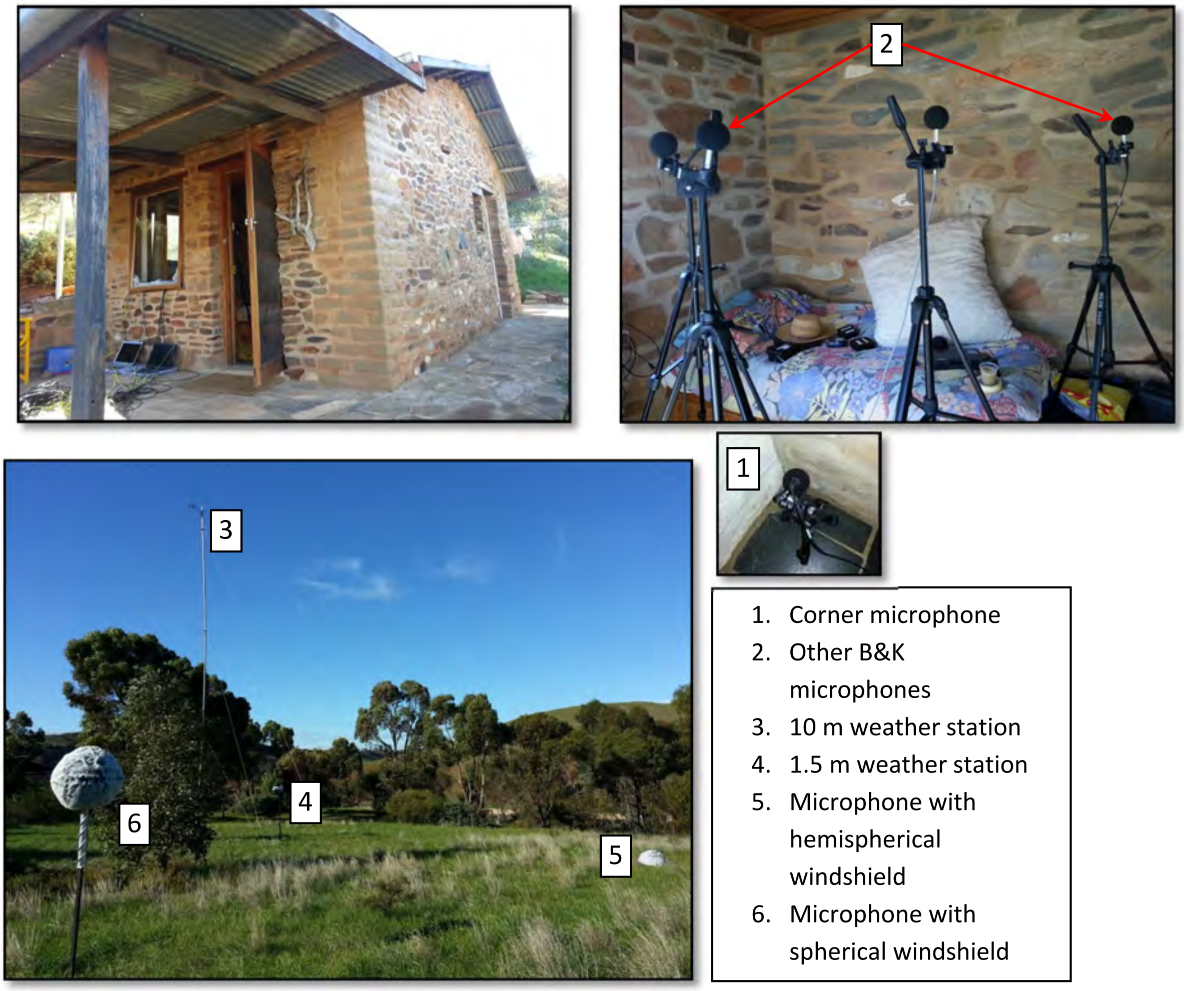


Figure 24 – Indoor measurement results for East residence (second set).

4.7 East 2 site

The East 2 residence is located 8.7 km from the closest wind turbine and this location was not used in the EPA study. The closest wind turbine to this measurement site is ‘BJ’, which is 2.5 km from the residence. The downwind direction from the closest wind turbine to the residence is between 223° and 313°. For the indoor measurements, a small cottage was used and is pictured in Figure 25. This cottage is separated from the main residence by about 10 m. The walls of the cottage are constructed from stone and the roof consists of corrugated sheet steel. The ceiling is constructed from wooden panels and there are two medium-sized windows, one of which faces towards the wind farm. There were no electrical appliances operating in the cottage for the duration of the measurements aside from our instrumentation. The zoning for this location is “rural industrial”. The instrumentation set-up is shown in Figure 25.



1. Corner microphone
2. Other B&K microphones
3. 10 m weather station
4. 1.5 m weather station
5. Microphone with hemispherical windshield
6. Microphone with spherical windshield

Figure 25 – Instrumentation set-up at East 2 residence.

The microphones used for the indoor averaging are labelled 1 and 2, where the corner microphone was positioned in the room corner closest to the wind farm. The outdoor instrumentation was located in an open field about 30 m from the main residence and 40 m from the cottage. This location was chosen to minimise interference from obstacles such as the house and trees, which would cause eddy generation, shielding and wind-induced noise.

The following results were collected over 6 days from 4th June – 10th June 2013. The outdoor results are not presented in this analysis because the power cable connected to the SVAN 958 sound level meter failed. Data were still measured outdoors using a National Instruments NI 9234 data acquisition device but as the noise floor of the NI 9234 device was 27 dBA, these data are not presented here. The data plotted in Figure 26 and Figure 27 show the average noise levels for the three indoor microphones pictured in Figure 25.

According to Figure 26 (a) and (b), there were several occasions where the indoor limit for wind turbine hosts of 30 dB(A) recommended by the SA EPA (2009) was exceeded, particularly when the wind speed at hub height was greater than 12m/s and the residence was downwind from the wind farm. It should be noted that the residents at this location are not wind turbine hosts. On the other hand, the corresponding local wind speed at a height of 10 m was between 6 m/s to 8 m/s and hence there was a significant amount of wind-induced noise which contributed to the high A-weighted level indoors. Therefore in this instance it is almost impossible to separate wind turbine noise and wind-induced noise unless a detailed analysis of the relative contributions of each third-octave band is undertaken.

The difference between the overall indoor A-weighted level (L_{Aeq}) and the indoor A-weighted level exceeded for 90% of the time (L_{A90}) is shown in Figure 26 (c) and (d). The average difference between these metrics was calculated to be 3.3 dB(A). The difference is consistently greater than 4 dB(A) for downwind conditions with hub height wind speeds greater than 12 m/s. However, the corresponding local wind speed at a height of 10 m was between 6 m/s to 8 m/s and therefore it is difficult to determine the relative contributions of wind turbine noise and wind-induced noise as mentioned above.

The indoor C-weighted results shown in Figure 26 (c) and (d) indicate the L_{Ceq} does not exceed the 60 dB(C) level for the duration of the measurement period and thus a low-frequency noise issue is not indicated by this metric. Nevertheless, the highest C-weighted levels were recorded under downwind conditions. According to Figure 26 (e) and (f), the difference between the overall C- and A-weighted can be as high as 30 dB, signifying a potential low-frequency noise issue.

For downwind conditions where the hub height wind speed > 12 m/s and the local wind speed at a height of 10 m was between 6 m/s to 8 m/s, there is also a significant increase in the levels of infrasound as shown in Figure 27 (a) and (b). These results indicate that the increased infrasound could either be attributed to the wind farm or wind-induced noise or most likely both of these sources. The overall G-weighted levels are just below 70 dB(G) for all measurements, which is lower than the 85 dB(G) audible threshold (ISO 7196, 1995). This may imply that the infrasound would not be audible to a person with normal hearing. However, it does not mean that the infrasound is not detectable (Salt & Lichtenhan, 2014), especially when the crest factor (ratio of peak to rms) of the sound is considered, as discussed in Section 4.1.

Data are plotted against the Danish low-frequency guidelines in Figure 27 (c) and (d) and over 20 measurements of 10 minute duration exceed the 20 dB(A) limit. All of these data points were measured during downwind conditions when the wind speed at hub height was greater than 8 m/s and the local wind speed at a height of 10 m was between 6 m/s to 8 m/s. These results suggest that there could be an indoor low-frequency noise issue at this location for specific wind conditions. On the other hand, it is difficult to determine if this issue is caused by the wind farm or wind-induced noise and hence further investigation into the relative contributions of different frequencies would be required to gain more insight.

The DEFRA criteria were also not met for a number of third-octave bands as indicated in Figure 27 (c) and (d). In most cases where the DEFRA criteria were not satisfied, the residence was downwind from the wind farm and the hub height wind speed was greater than 8 m/s and the local wind speed at a height of 10 m was between 6 m/s to 8 m/s. The worst cases showed that only 54% of the third-octave bands from 10 Hz to 160 Hz met the DEFRA criteria. Once again, further analysis into the spectral characteristics would be required to determine if the exceedences were caused by wind farm noise or wind-induced noise.

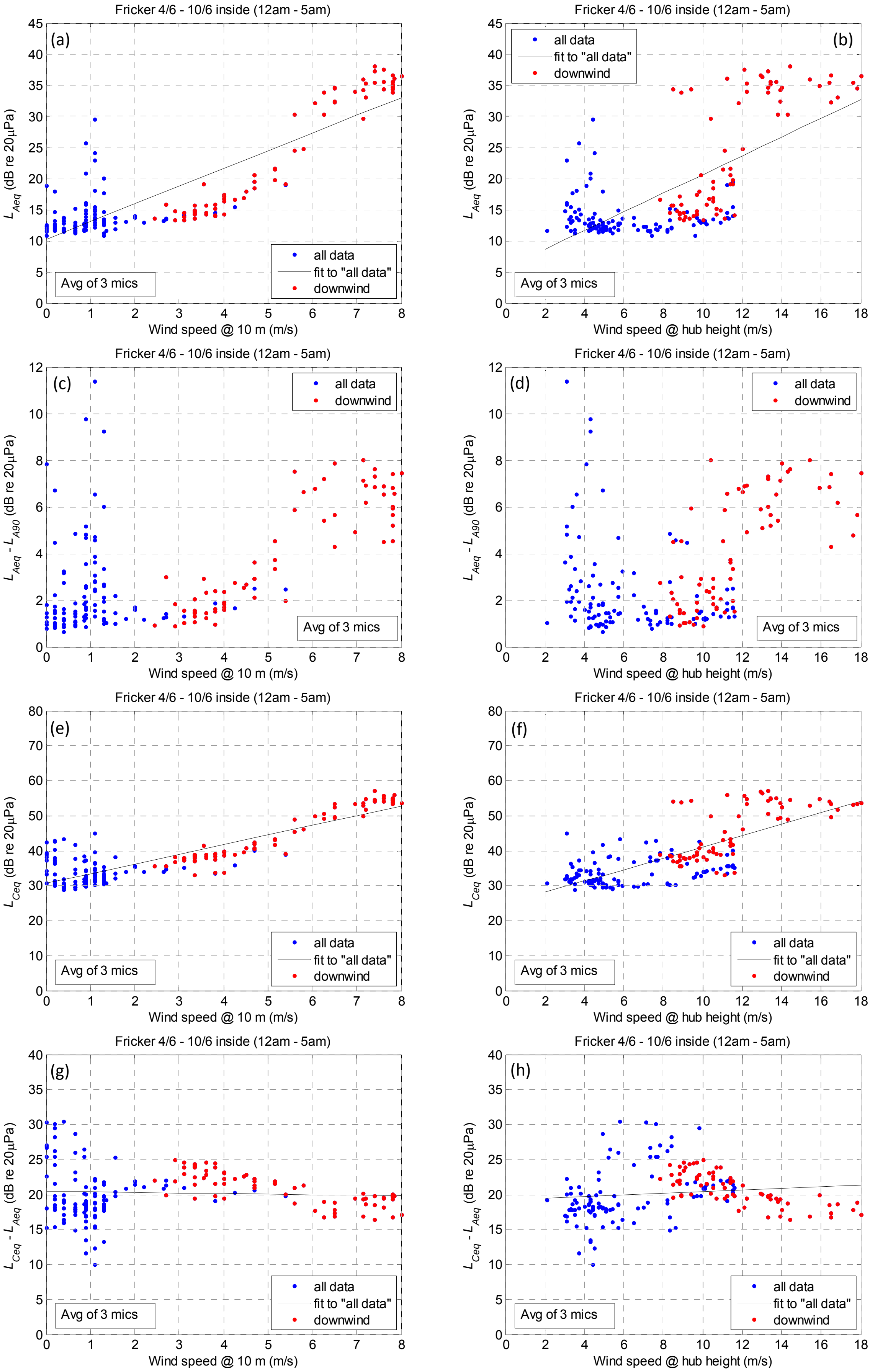


Figure 26 – Indoor measurement results for East 2 residence (first set).

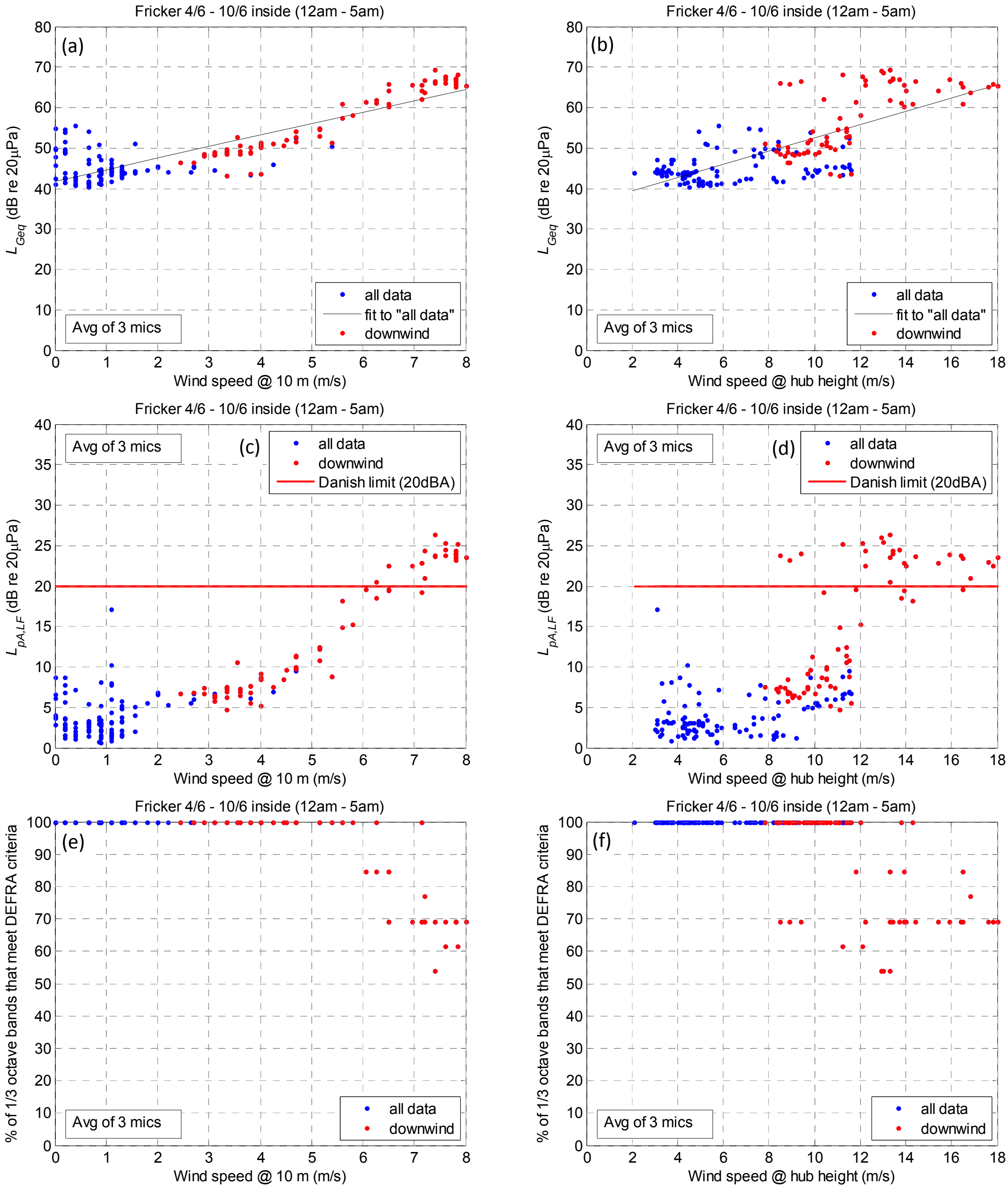
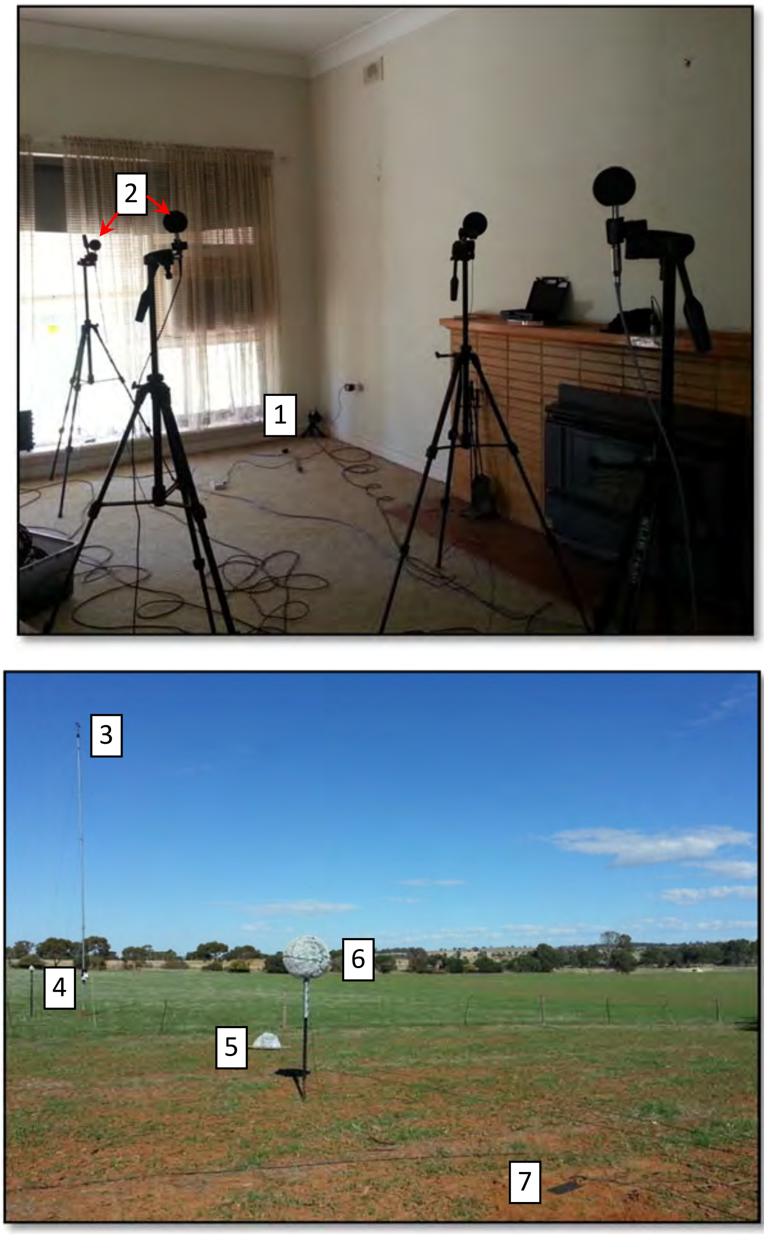


Figure 27 – Indoor measurement results for East 2 residence (second set).

4.8 South West site

The residence at which the measurements were taken was not used in the EPA study. The closest wind turbine to this measurement site is ‘EC’, which is 2.7 km from the residence. The downwind direction from the closest wind turbine to the residence is between 18° and 108°. The residence was built in 1911 and an extension was added in 1960. The instrumentation was set up in the extension section, which faces the wind farm. The walls of this extension are constructed from double brick. The walls of the original house are constructed from stone and the roof of the house and extension consists of corrugated sheet steel. There is one large window in the room where the measurements were taken and it faces the wind farm. The ceiling material is plasterboard/gyprock in the room where the instruments were located. There is no wall insulation but the ceiling space has pink bats in four rooms, including the room with the instrumentation. The instrumentation set-up is shown in Figure 28.



1. Corner microphone
2. Other B&K microphones
3. 10 m weather station
4. 1.5 m weather station
5. Microphone with hemispherical windshield
6. Microphone with spherical windshield
7. Microphone with box windshield

Figure 28 – Instrumentation set-up at South West residence.

The microphones used for the indoor averaging are labelled 1 and 2, where the corner microphone was positioned in the room corner closest to the wind farm. The outdoor instrumentation was located as shown.

The outdoor microphones were located about 30 m from the residence in a large open field. The weather stations were located in an adjacent field about 40 m from the residence. Positioning the outdoor instrumentation in this location minimised the influence of shielding, eddies and wind-induced noise associated with obstacles such as the house and trees.

The results presented in the following analysis were collected over one week from 8th May – 13th May 2013. The outdoor results shown in Figure 29 were obtained using a single microphone mounted on a ground board and protected from the wind by a secondary hemispherical windshield. The data plotted in Figure 30 and Figure 31 show the average noise levels for the three indoor microphones pictured in Figure 28.

Considering the overall A-weighted results shown in Figure 29 (a) and (b), there are many occasions where the measured levels exceeded the outdoor criteria of 40 dB(A). It can also be seen that the regression curve obtained by plotting the overall A-weighted results against hub height wind speed exceeds the 40 dB(A) criteria. Most of the data points exceeding 40 dB(A) are associated with conditions where the wind speed at hub height was greater than 8 m/s and the local wind speed at a height of 10 m was between 2 m/s and 6 m/s. However, since the A-weighted level can vary significantly for a given local wind speed at a height of 10 m, the noise levels exceeding 40 dB(A) cannot be attributed to wind-induced noise for wind speeds at a height of 10 m of less than 5 m/s. For example, the A-weighted level can be as low as 32 dB(A) and as high as 47 dB(A) for a local wind speed of 4 m/s at a height of 10 m and this variation is most likely explained by wind turbine noise being the major contributor. It should be noted that all data points over 40 dB(A) with identified vehicle and animal noise sources have been eliminated from the results and thus it is reasonable to assume that the increased levels can be attributed to the wind farm.

The outdoor C-weighted results shown in Figure 29 (c) and (d) indicate that the levels only exceed 60 dB(C) by a small amount and therefore, a low-frequency noise problem is not indicated by this metric. On the other hand, numerous data points exceed the $L_{Ceq} - L_{Aeq} = 20$ dB criterion as shown in Figure 29 (e) and (f). Many of these data points were recorded during downwind conditions for hub height wind speeds greater than approximately 6 m/s and local wind speeds at a height of 10 m of between 1 m/s and 4 m/s. The low local wind speeds imply that wind-induced noise would be minimal for these measurements. Hence, a low-frequency noise issue is indicated by this metric and it is probable that it is associated with the wind farm.

The G-weighted outdoor and indoor levels shown in Figure 29 (g) and (h) and Figure 31 (a) and (b), respectively, indicate that the $L_{Geq} < 68$ dB(G) for all measurements which is lower than the 85 dB(G) audible threshold (ISO 7196, 1995). This may imply that the infrasound would not be audible to a person with normal hearing. However, it does not mean that the infrasound is not detectable (Salt & Lichtenhan, 2014), especially when the crest factor (ratio of peak to rms) of the sound is considered. This is because the threshold levels were determined for single, steady tones which are very different in character to wind farm infrasound and low-frequency sound.

According to Figure 30 (a) and (b), there were several occasions where the indoor limit for wind turbine hosts of 30 dB(A) recommended by the SA EPA (2009) was exceeded, particularly when the wind speed at hub height was greater than 9m/s and the local wind speed at a height of 10 m was between 2 m/s and 6 m/s. There was also a large spread in the overall A-weighted indoor levels from 10 dB(A) to 38 dB(A). Even for a local wind speed at a height of 10 m of 4 m/s, the indoor A-weighted level varied between 16 dB(A) and 38 dB(A), which shows that wind-induced noise was not responsible for the high indoor noise levels at this residence. Indoor noise levels of 38 dB(A) are particularly excessive, especially since the no observed health effect limit for *outdoor* noise is 30 dB(A) according to the WHO (2009).

The difference between the overall indoor A-weighted level (L_{Aeq}) and the indoor A-weighted level exceeded for 90% of the time (L_{A90}) is shown in Figure 30 (c) and (d). The average difference between these metrics was calculated to be 3 dB(A). Even between the hours of 12am and 5am, where the contribution from extraneous noise sources is expected to be minimal, this difference can be greater than 8 dB(A). It should be noted that all audio files which were contaminated by vehicle and animal noise were eliminated from this analysis. Therefore, it is probable that the large difference between the L_{Aeq} and the L_{A90} is caused by wind turbine noise, which can be highly variable with time depending on the atmospheric conditions. If this were the case, using the L_{A90} to determine compliance would lead to erroneous results.

The indoor C-weighted results shown in Figure 30 (e) and (f) reveal that the C-weighted levels do not exceed 60 dB(C) and thus a low frequency noise issue is not indicated by this metric. On the other hand, the indoor difference between the overall C- and A-weighted levels can reach 33 dB, which is much higher than the recommended value of $L_{Ceq} - L_{Aeq} < 20$ dB, indicating that there is a low-frequency noise problem according to this metric. These cases correspond to hub height wind speeds greater than 9 m/s and local wind speeds at a height of 10 m of between 1 m/s and 4 m/s. This suggests that the presence of low frequency noise indicated by this metric can be attributed to the wind farm.

The Danish low-frequency guidelines were exceeded on numerous occasions at this residence as shown in Figure 31 (c) and (d). In all cases except one, the wind speed at hub height was greater than 8 m/s and the local wind speed at a height of 10 m was between 2 m/s and 6 m/s. This implies that the increased levels in low-frequency noise can be attributed to the wind farm. Further evidence that high levels of low-frequency noise were measured at this residence is given by comparison to the DEFRA criteria. Figure 31 (e) and (f) show that the DEFRA criteria were only partially met on a number of occasions and that all but one of these measurements were recorded under downwind conditions, where the wind speed at hub height was greater than 8 m/s and the local wind speed at a height of 10 m was between 2 m/s and 6 m/s.

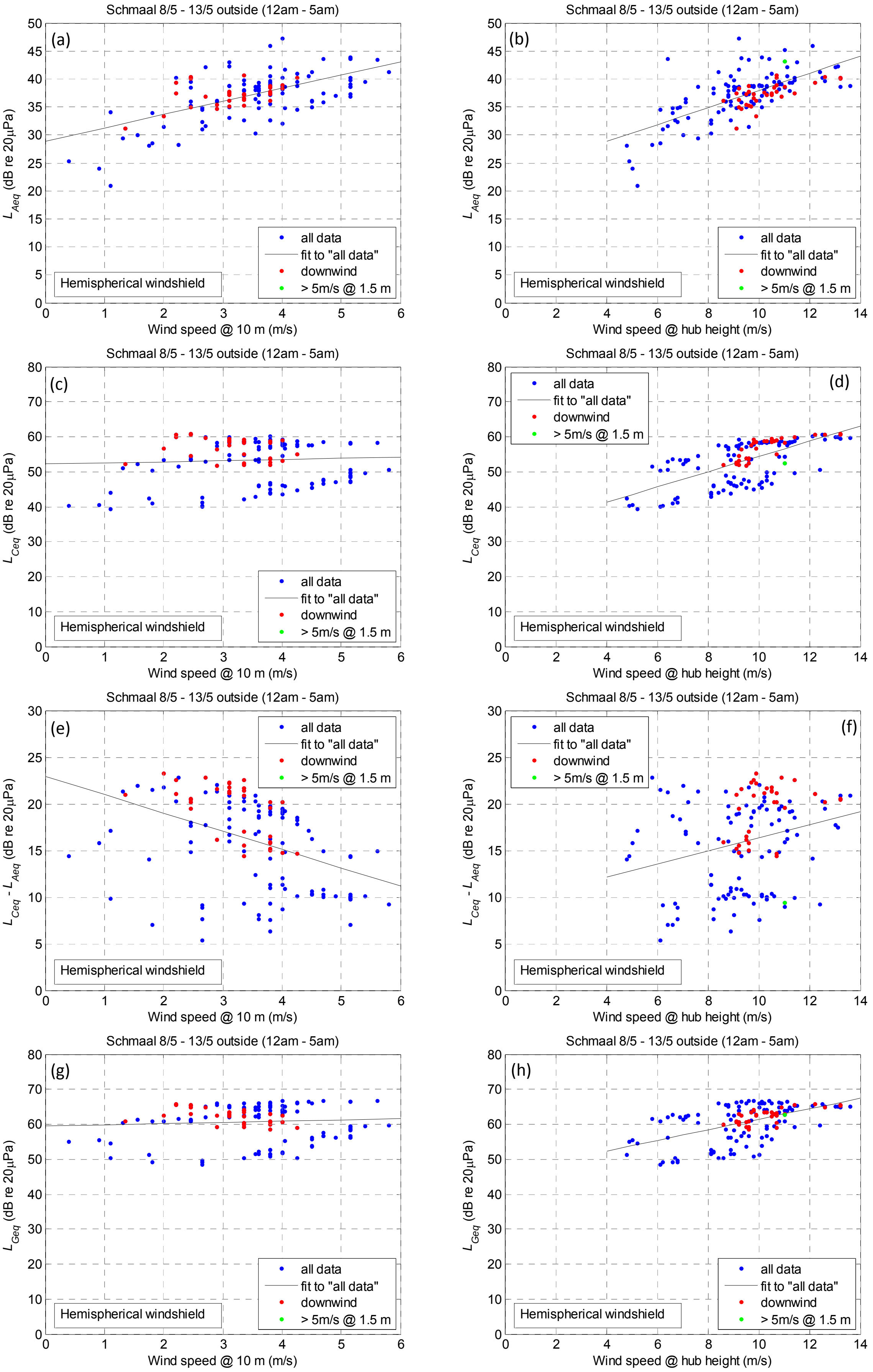


Figure 29 – Outdoor measurement results for South West residence.

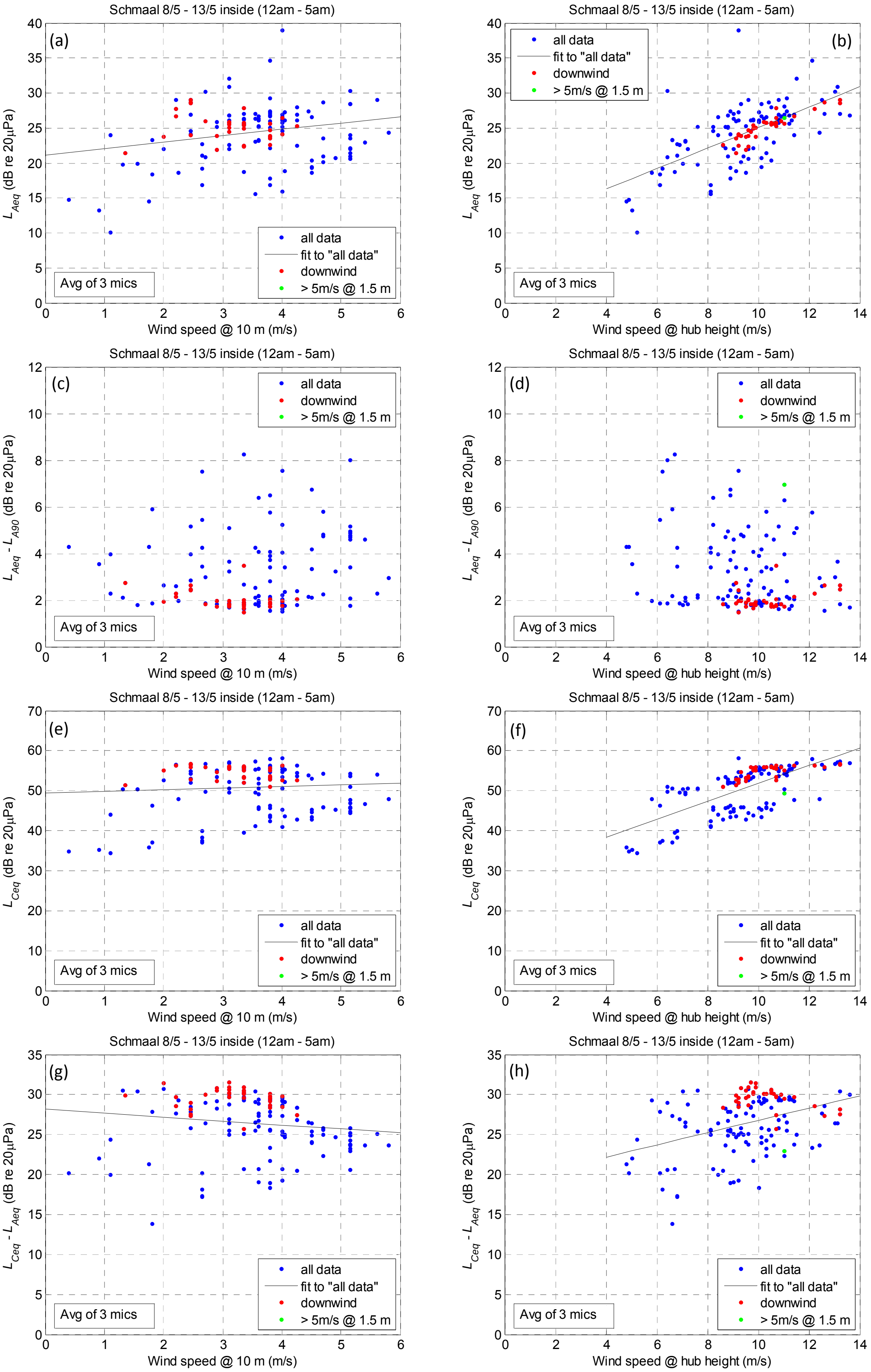


Figure 30 –Indoor measurement results for South West residence (first set).

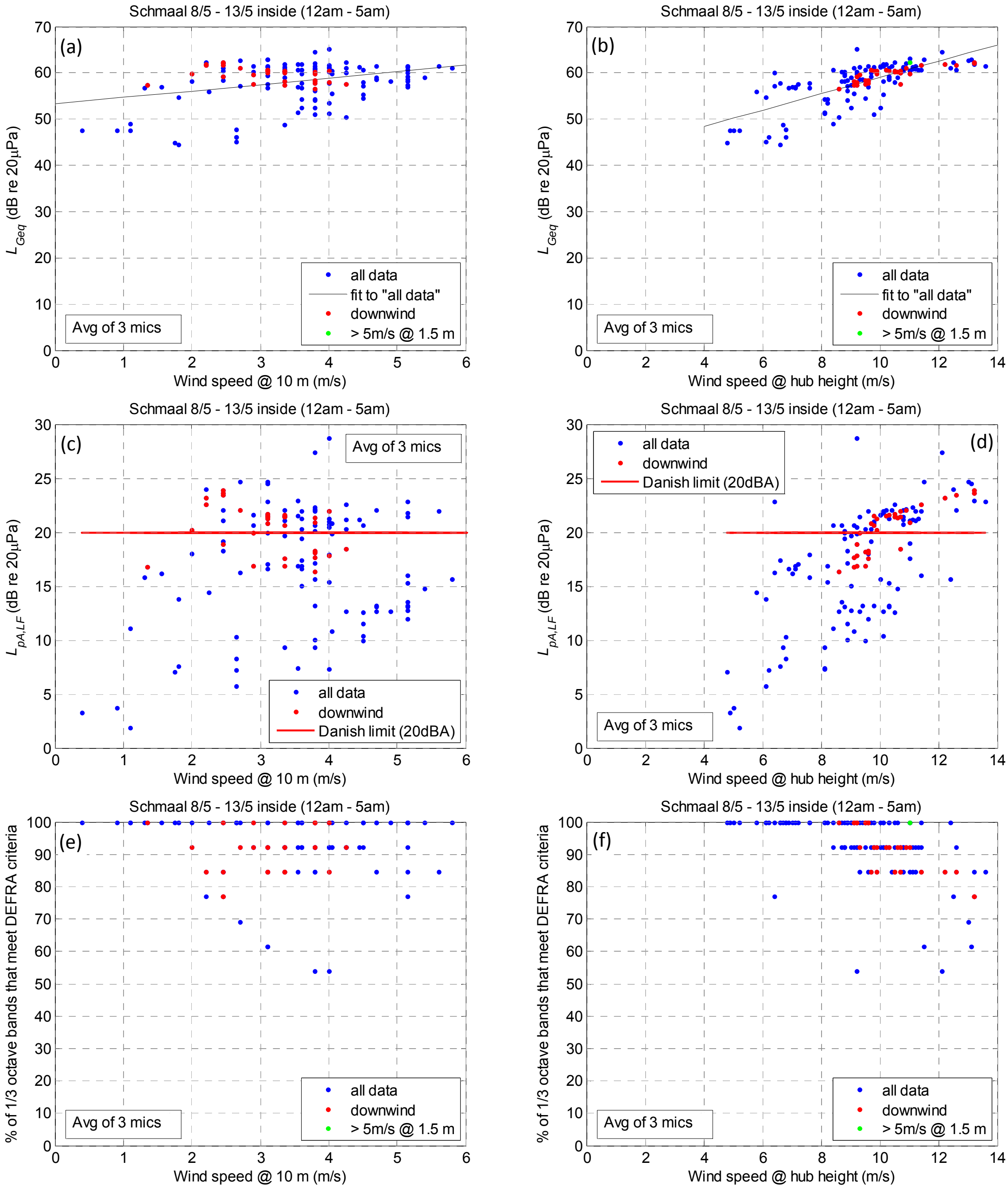


Figure 31 –Indoor measurement results for South West residence (second set).

5 Shutdowns

The following plots show the unweighted sound pressure level for times related to when the wind farm was shut down. Comparisons are made between measurements that were taken before the shutdown (three 10-minute averages), during the shutdown and after the shutdown (three 10-minute averages) as well as for other measurement times where the wind conditions at hub height and at the residence were similar to those that occurred during shutdown. The conditions were matched based on the criteria that the wind speed at hub height should be within +/-10%, the wind speed at a height of 1.5 m should be within +/-10% and the wind direction at hub height should be within +/-22.5°. These tolerances were reduced in some cases, where there were a large number of operational conditions that matched the shutdown conditions. The location at which the measurements were recorded was dependent on where the monitoring gear was positioned at the time of the shutdown. The monitoring gear was always located at one residence at a given time and since we were not aware of when shutdowns would occur, Shutdown 5 was not recorded. The shutdown times and distance and direction of the nearest turbine relative to the residence are shown in Table 1.

Table 1 – Locations of instrumentation for wind farm shutdowns

	Date/time	Location	Distance from nearest wind turbine (km)	Downwind direction (°)
Shutdown 1	1/5, 20:10 – 21:00	Township	3.5	88
Shutdown 2	30/5, 19:10 – 20:00	Township	3.5	88
Shutdown 3	5/6, 20:40 – 21:30	East 2	8.7	268
Shutdown 4	10/6, 5:10 – 6:00	East 2	8.7	268
Shutdown 6	14/6, 20:00 – 20:50	West	2.5	98

5.1 Shutdown 1 – Township site

The unweighted 10-minute averaged third-octave spectra for the shutdown and operational cases are shown in Figure 32 (a-d). The curve labelled “ISO 389-7” corresponds to the generally accepted threshold of hearing for normal ears subjected to steady tonal noise. The outdoor and indoor noise levels measured during the shutdown cases were consistently lower than those measured when the wind farm was operating. This can be observed for the entire frequency range from 1 Hz – 1000 Hz. Comparison between Figure 32 (a) and (b) and Figure 32 (c) and (d) reveals that the increased noise levels can also be observed for operational conditions selected based on matching wind speed conditions. This refutes the argument that the increased noise levels before and after shutdown can be attributed to differences in the wind conditions.

The most significant difference in the spectra occurs for the 50 Hz third-octave band, where the sound pressure level difference between shutdown and operational cases can be more than 25 dB for both outdoor and indoor measurements. This difference is much larger than that which was shown in the EPA report (2013), where the outdoor operational levels in the 50 Hz third-octave band were closer to 45 dB (instead of the 58 dB shown in Figure 32a) and the shutdown levels are similar to those shown in Figure 32 (a) and (c) giving a difference of approximately 15 dB. The indoor levels reported by the EPA (2013) were also much lower than those presented in Figure 32 (b) and (d) and were close to 30 dB. Contrary to the EPA report (2013) findings, the data in Figure 32 shows that the noise in the 50 Hz third-octave band, associated with operational conditions, would be audible both indoors and outdoors to a person with normal hearing according to ISO 389-7 (2005). In addition, the peak in the 50 Hz third-octave band is more than 15 dB higher than the level in the adjacent third-octave bands for the indoor results. According to guidelines specified in standards such as NZS 6808:2010 (2010) and ANSI S12.9 - Part 4 (2005), this would be classified as a tone and hence an adjustment to the allowable wind farm noise limits would be required. According to the EPA (2009), a penalty of 5 dB(A) would need to be added to the measured noise level in the case of identified tonality. The results in this report suggest that this would lead to non-compliance at the Township residence, in contrast to the EPA study (EPA, 2013) results, which indicate that the wind farm would still be compliant.

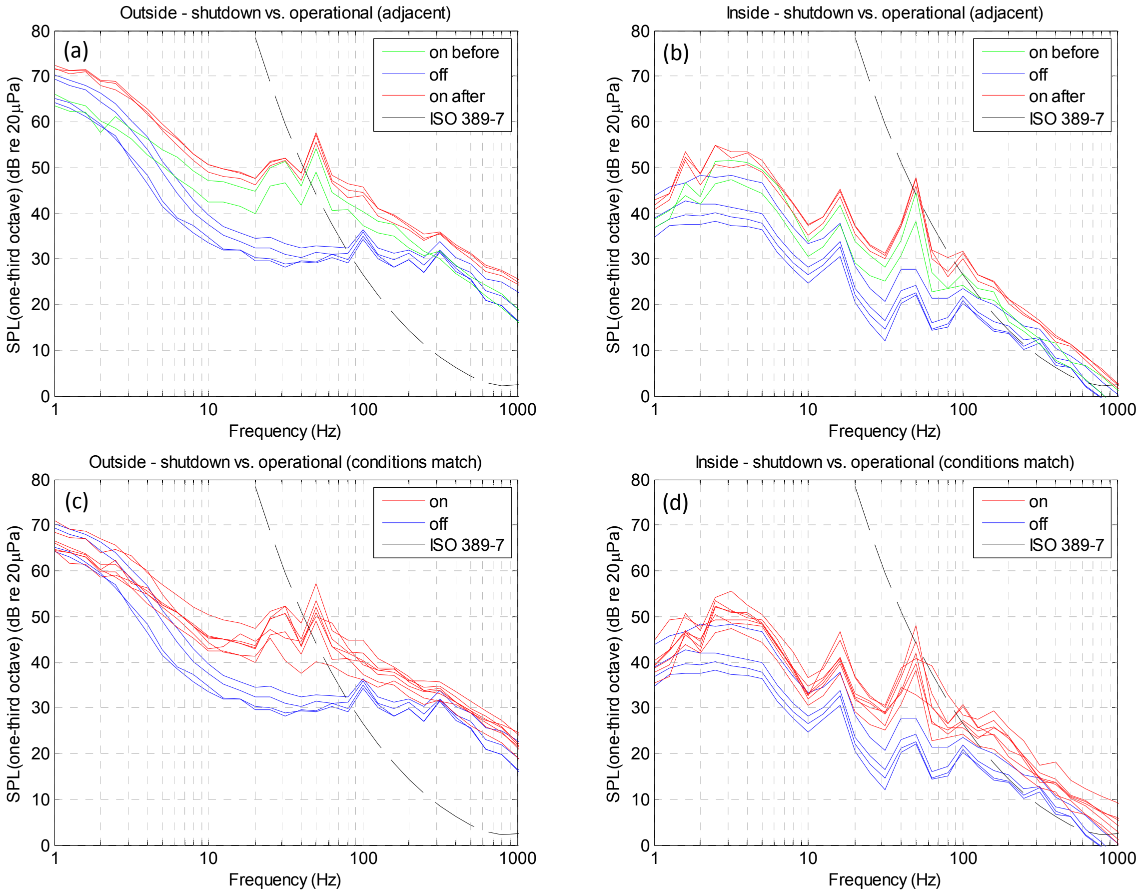


Figure 32 – Wind farm shutdown vs. operational, 1st May, Kruse residence (SHUTDOWN 1).

The outdoor results shown in Figure 32 (a) and (c) also indicate that the sound pressure level in the 31.5 Hz third-octave band is higher when the wind farm is operating. On the other hand, the indoor results shown in Figure 32 (b) and (d) do not show a peak in the sound pressure level at this frequency. It is possible that the noise level in this third-octave band varies with room position due to the presence of room resonances and thus the average results would not reflect the worst case scenario for indoor noise. The large difference in the sound pressure level indoors relative to outdoors was also shown in the EPA report (2013) for the 31.5 Hz third-octave band. Another characteristic that can be attributed to wind farm operation are the peaks in the infrasonic frequency range which appear to correspond to harmonics of the blade-pass frequency. Additionally, a significant peak is evident in the 16 Hz third-octave band for the indoor results. While this peak is present for both operational and shutdown conditions, the level is consistently higher when the wind farm is operating, by as much as 15 dB. It is believed that there is a structural resonance of the residence at this frequency which is excited by both wind induced noise and wind farm noise. It has been found previously that structural resonances occur in the range of 12-30 Hz, according to data measured for several different housing structures (Hubbard, 1982).

Given that the nearest wind turbine is located in the direction of 88° from the Township residence, it can be seen that the residence was downwind from the wind farm for all measurements according to Table 2. The wind speed measured at a height of 1.5 m in the vicinity of the residence was relatively low and did not exceed 2.7 m/s. The wind speed at hub height was above the cut-in speed of 3.5 m/s (Vestas, n.d.) but did not reach the rated speed of 15 m/s (Vestas, n.d.).

Table 2 – Wind conditions for shutdown vs. operational, 1st May, Kruse residence (SHUTDOWN 1).

SHUTDOWN						
	wind speed @1.5 m (m/s)	wind dir @1.5 m (°)	wind speed @10m (m/s)	wind dir @10 m (°)	wind speed @hub (m/s)	wind dir @hub (°)
min	1.6	135.0	3.4	135.0	9.7	125.5
max	2.0	135.0	4.3	135.0	11.7	129.4
	ADJACENT					
min	1.6	135.0	3.6	135.0	9.8	124.7
max	2.7	135.0	4.7	135.0	14.2	131.0
	CONDITIONS MATCH					
min	1.6	135.0	3.1	135.0	8.8	122.6
max	2.0	135.0	4.3	146.3	12.7	134.1

Overall levels were calculated from 10-minute data samples, which were weighted using the weightings discussed in Section 3. The outdoor results are shown in Table 3 and the indoor results are shown in Table 4. In general, the levels measured during wind farm operation were higher than those measured when the wind farm was shutdown regardless of the applied weighting function.

Table 3 – Outdoor acoustic descriptors for shutdown vs. operational, 1st May, Kruse residence (SHUTDOWN 1).

SHUTDOWN				
	L_{Aeq}	L_{Ceq}	L_{Geq}	L_{Ceq}- L_{Aeq}
min	30.5	40.9	45.6	9.9
max	35.2	48.9	51.6	13.6
ADJACENT				
min	32.8	48.9	46	13.6
max	38.1	58.8	63	21.2
CONDITIONS MATCH				
min	32.8	48.3	55.8	13.2
max	37.4	58.4	62.5	21.9

A potential low-frequency noise issue is indicated by the maximum indoor value of $L_{Ceq} – L_{Aeq}$, which is over 6 dB higher than the recommended value of 20 dB when the wind farm is operating. The presence of low-frequency noise is further indicated by the fact that the noise level in one of the third-octave bands exceeded the allowable limit specified DEFRA criteria. The EPA study (EPA, 2013) found that the wind farm met the DEFRA criteria at all times but only one 10-minute measurement was considered in the EPA report both before and after the shutdown as opposed to the three measurements before and after considered in this study. The indoor limit specified by the Danish guidelines for indoor low-frequency noise is not exceeded but there is a significant difference in the value of $L_{pA,lf}$ when the wind farm was operational compared to when it was shutdown.

Table 4 - Indoor acoustic descriptors for shutdown vs. operational, 1st May, Kruse residence (SHUTDOWN 1).

SHUTDOWN							
	L_{Aeq}	L_{A90}	L_{Ceq}	L_{Geq}	L_{Ceq}- L_{Aeq}	$L_{pA,lf}$	DEFRA
min	12.5	8.8	29.1	40.2	16.7	0.3	100.0
max	21.1	12.0	38.2	47.8	19.3	11.2	100.0
	ADJACENT						
min	17.1	9.3	38.2	43.5	17.1	9.7	92.3
max	21.9	18.9	48.1	54.8	26.3	18.4	100.0
	CONDITIONS MATCH						
min	17.1	9.3	39.5	47.2	19.8	9.6	92.3
max	24.0	18.2	48.1	55.4	26.9	18.2	100.0

5.2 Shutdown 2 – Township site

The unweighted indoor third-octave spectra for the shutdown and operational cases are shown in Figure 33 (a) and (b). Indoor data are presented exclusively in this section since the weather forecast predicted heavy rain for this measurement period and instruments left out in this weather would have been at risk of permanent damage. The indoor noise levels measured during the shutdown cases were generally lower than those measured when the wind farm was operating, particularly for third-octave band frequencies below 80 Hz. It should be noted that the difference is less significant than that which was observed in Figure 32 despite the fact that the location is the same. These observations are similar for measurements acquired before and after the shutdown compared to those for which the conditions were matched, as shown in Figure 33 (a) and (b).

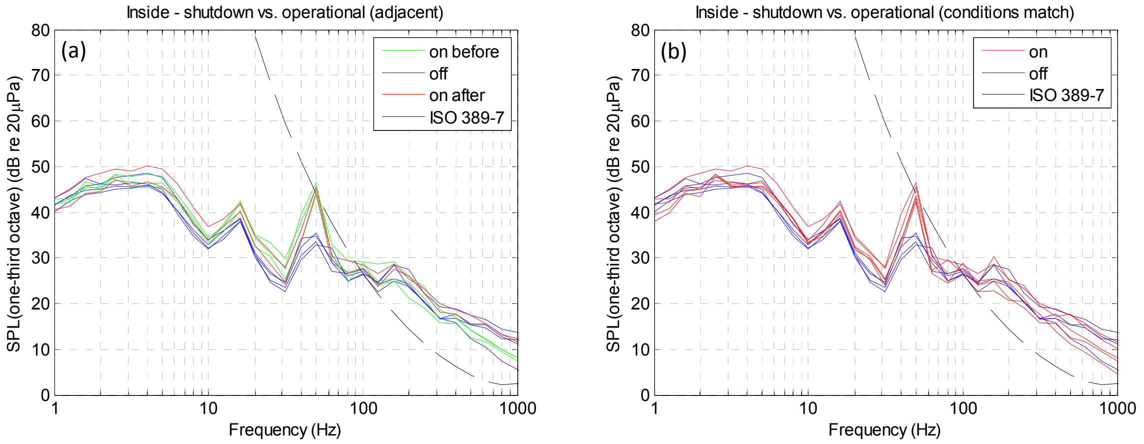


Figure 33 – Wind farm shutdown vs. operational 30th May, Kruse residence (SHUTDOWN 2).

The most significant difference in the spectra between shutdown and operational conditions occurs for the 50 Hz third-octave band, where the sound pressure level difference can be as large as 10 dB for the indoor measurements. This difference is lower than that which was observed during the first shutdown for the indoor measurements. Nevertheless, the indoor noise in this third-octave band associated with operational conditions would be audible to a person with normal hearing according to ISO 389-7 (2005). In addition, the peak in the 50 Hz third-octave band is more than 15 dB higher than the level in the adjacent third-octave bands for the indoor results. According to guidelines specified in standards such as NZS 6808:2010 (2010) and ANSI S12.9 - Part 4 (2005), this would be classified as a tone and hence an adjustment to the allowable wind farm noise limits would be required. The magnitude of this adjustment and its effect on compliance was discussed in Section 5.1.

Other characteristics that can be attributed to wind farm operation are the peaks in the infrasonic frequency range, which appear to correspond to harmonics of the blade-pass frequency. Additionally, a significant peak is evident in the 16 Hz third-octave band. While this peak is present for both operational and shutdown conditions, the level is consistently higher when the wind farm is operating. It is believed that there is a structural resonance of the residence at this frequency which is excited by both wind induced noise and wind farm noise. It has been found that structural resonances occur in the range of 12-30 Hz, according to data measured for several different housing structures (Hubbard, 1982).

Given that the nearest wind turbine is located in the direction of 88° from the residence, it can be seen that the residence was not downwind from the wind farm for any of the measurements according to Table 5. The wind speed measured at a height of 1.5 m in the vicinity of the residence was relatively low and did not exceed 1.6 m/s. The wind speed at hub height was above the cut-in speed of 3.5 m/s (Vestas, n.d.) but did not reach the rated speed of 15 m/s (Vestas, n.d.). Hence, the most significant difference in the wind conditions for Shutdown 2 compared to Shutdown 1 was the wind direction at hub height.

Table 5 - Wind conditions for shutdown vs. operational, 30th May, Kruse residence (SHUTDOWN 2).

	wind speed @1.5 m (m/s)	wind dir @1.5 m (°)	wind speed @10m (m/s)	wind dir @10 m (°)	wind speed @hub (m/s)	wind dir @hub (°)
SHUTDOWN						
min	1.3	45.0	2.9	33.8	11.2	20.3
max	1.6	56.3	3.4	45.0	12.8	25.6
ADJACENT						
min	1.1	45.0	2.7	45.0	11.1	20.2
max	1.6	56.3	3.1	45.0	13.6	24.8
CONDITIONS MATCH						
min	1.3	45.0	2.5	33.8	11.1	18.8
max	1.6	67.5	3.1	45.0	13.9	25.1

Comparison between Figure 32 (b) and (d) and Figure 33 (a) and (b) indicates that the difference between shutdown and operational conditions is much more significant when the residence is located downwind from the wind farm. On the other hand, there is only a small difference in the sound pressure level in the 50 Hz third-octave band for operational conditions. The peak appears less significant in Figure 33 (a) and (b) because the background noise level was relatively higher during Shutdown 2 compared to Shutdown 1. This is most likely related to truck noise which was present in several of the audio files during the Shutdown 2 period. Given that truck noise is a regular occurrence at this residence due to operations at the nearby open-cut mine, it seems inconceivable that the wind farm shutdowns were not scheduled to occur between 12 am and 5 am, when this noise source would not be present and the effect of other extraneous noise sources would be much less.

Overall levels shown in Table 6 were calculated from 10-minute data samples, which were weighted using the weightings discussed in Section 3. In general, the levels measured during wind farm operation were higher than those measured when the wind farm was shutdown, regardless of the applied weighting function. A potential low-frequency noise issue is indicated by the maximum indoor value of $L_{Ceq} – L_{Aeq}$, which is higher than the recommended value of 20 dB when the wind farm is operating. The presence of low-frequency noise is further indicated by the fact that the noise level in one of the third-octave bands exceeded the allowable limit specified DEFRA criteria. The EPA study (EPA, 2013) found that the wind farm met the DEFRA criteria at all times but only one 10-minute measurement was considered both before and after the shutdown as opposed to the three measurements before and after considered in this study. The indoor limit specified by the Danish guidelines for indoor low-frequency noise is not exceeded but there is a significant difference in the value of $L_{pA,lf}$ when the wind farm was operational compared to when it was shutdown.

Table 6 - Indoor acoustic descriptors for shutdown vs. operational, 30st May, Kruse residence (SHUTDOWN 2).

SHUTDOWN							
	L_{Aeq}	L_{A90}	L_{Ceq}	L_{Geq}	L_{Ceq}- L_{Aeq}	$L_{pA,lf}$	DEFRA
min	21.4	14.1	38.6	47.9	14.2	9.7	100.0
max	24.8	19.1	39.8	49.0	18.4	10.4	100.0
ADJACENT							
min	21.4	17.1	44.1	50.1	20.5	14.7	92.3
max	24.7	19.5	46.9	52.1	24.1	16.8	92.3
CONDITIONS MATCH							
min	20.3	16.7	42.8	49.3	19.3	13.0	92.3
max	24.7	19.4	46.9	52.1	24.1	16.8	100.0

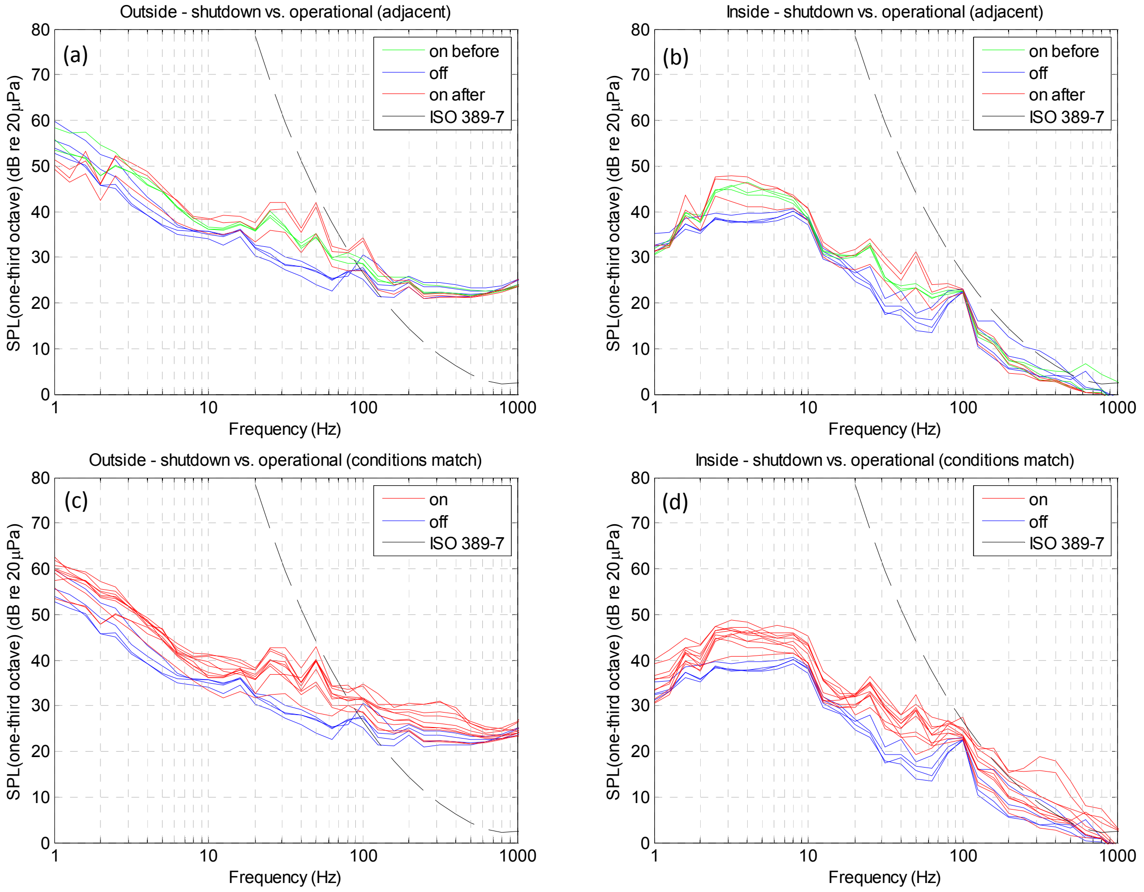
5.3 Shutdown 3 – East 2 site

The unweighted 10-minute averaged third-octave spectra for the shutdown and operational cases are shown in Figure 34 (a-d). The outdoor and indoor noise levels measured during the shutdown cases were consistently lower than those measured when the wind farm was operating. This can be observed for the majority of frequencies over the range from 1 Hz – 1000 Hz. Comparison between Figure 34 (a) and (b) and Figure 34 (c) and (d) reveals that the increased noise levels can also be observed for operational conditions selected based on matching wind speed conditions. This refutes the argument that the increased noise levels before and after shutdown can be attributed to differences in the wind conditions.

The most significant difference in the spectra occurs for the 50 Hz third-octave band, where the sound pressure level difference between shutdown and operational cases can be higher than 15 dB for both outdoor and indoor measurements. The plots shown in Figure 34 indicate that the outdoor noise in the 50 Hz third-octave band is close to the audibility threshold for a person with normal hearing, which is defined in ISO 389-7 (2005). However, since wind turbine noise is highly variable with time, it is expected that peak noise levels would be higher than the 10-minute average levels. Hence, noise in the 50 Hz third-octave band is likely to be audible outside and possibly inside to a person with normal hearing according to ISO 389-7 (2005).

The outdoor and indoor results shown in Figure 34 (a-d) also indicate that the sound pressure level in the 25 Hz and 31.5 Hz third-octave bands is higher when the wind farm is operating. Another characteristic that can be attributed to wind farm operation are the peaks in the infrasonic frequency range which appear to correspond to harmonics of the blade-pass frequency. These peaks are more noticeable indoors where the contribution from wind-induced noise would be expected to be much lower.

The peak in the 100 Hz third-octave band is most likely attributable to a transformer, which was located nearby the residence and this explains why it was present when the wind farm was shutdown. Nevertheless, it can be seen in Figure 34 (a), (c) and (d) that there may also have been a contribution from the wind farm to this third-octave band.


Outside - shutdown vs. operational (adjacent)

Inside - shutdown vs. operational (adjacent)

Outside - shutdown vs. operational (conditions match)

Inside - shutdown vs. operational (conditions match)

Figure 34 – Wind farm shutdown vs. operational 5th June, Fricker residence (SHUTDOWN 3).

Since the nearest wind turbine is located in the direction of 268° from the East 2 residence, it can be seen that the residence was downwind from the wind farm for all of the measurements according to Table 7. The wind speed measured at a height of 1.5 m in the vicinity of the residence was relatively low and did not exceed 2 m/s. The wind speed at hub height was above the cut-in speed of 3.5 m/s (Vestas, n.d.) but was at least 5 m/s lower than the rated speed of 15 m/s (Vestas, n.d.). Hence, due to the low hub height wind speeds, the sound pressure levels plotted in Figure 34 would be much lower than the maximum levels which would occur at this residence.

Table 7 – Wind conditions for shutdown vs. operational, 5th June, Fricker residence (SHUTDOWN 3).

SHUTDOWN						
	wind speed @1.5 m (m/s)	wind dir @1.5 m (°)	wind speed @10m (m/s)	wind dir @10 m (°)	wind speed @hub (m/s)	wind dir @hub (°)
min	1.1	281.3	2.5	292.5	7.5	303.6
max	1.8	292.5	3.4	292.5	8.7	309.6
ADJACENT						
min	0.7	292.5	2.2	292.5	7.9	295.5
max	2.0	292.5	3.4	292.5	9.5	310.0
CONDITIONS MATCH						
min	1.3	270.0	2.5	270.0	7.7	295.9
max	1.6	292.5	3.6	315.0	8.5	315.0

Overall levels were calculated from 10-minute data samples, which were weighted using the weightings discussed in Section 3. The outdoor results are shown in Table 8 and the indoor results are shown in

Table 9.

Table 8 – Outdoor acoustic descriptors for shutdown vs. operational, 5th June, Fricker residence (SHUTDOWN 3).

SHUTDOWN			
	L_{Ceq}	L_{Geq}	L_{Ceq}- L_{Aeq}
min	40.1	45.6	-0.3
max	44.2	48.1	2.0
ADJACENT			
min	43.1	49.5	1.9
max	46.9	52.3	6.3
CONDITIONS MATCH			
min	41.2	46.2	3.2
max	47.7	53.4	8.2

Table 9 – Indoor acoustic descriptors for shutdown vs. operational, 5th June, Fricker residence (SHUTDOWN 3).

SHUTDOWN							
	L_{Aeq}	L_{A90}	L_{Ceq}	L_{Geq}	L_{Ceq}- L_{Aeq}	$L_{pA,lf}$	DEFRA
min	11.9	10.9	30.6	42.8	18.2	1.4	100.0
max	13.9	11.7	33.2	45.7	20.2	3.4	100.0
ADJACENT							
min	11.8	10.8	32.9	44.2	20.4	2.5	100.0
max	14.7	11.9	37.5	47.8	24.6	6.2	100.0
CONDITIONS MATCH							
min	12.2	11.3	34.8	45.9	20.4	3.4	100.0
max	19.9	13.7	38.7	50.6	24.5	7.9	100.0

In general, the levels measured during wind farm operation were slightly higher than those measured when the wind farm was shutdown, regardless of the applied weighting function. The small differences between shutdown and operational conditions could be explained by the low hub height wind speeds associated with the shutdown period. Nevertheless, a potential low-frequency noise issue is indicated by the maximum indoor value of $L_{Ceq} - L_{Aeq}$, which is higher than the recommended value of 20 dB when the wind farm is operating.

5.4 Shutdown 4 – East 2 site

The unweighted 10-minute averaged third-octave spectra for the shutdown and operational cases are shown in Figure 35 (a-d). The outdoor and indoor noise levels measured during the shutdown cases were consistently lower than those measured when the wind farm was operating for the third-octave bands between 20 Hz and 63 Hz. For the indoor results, the noise levels were lower during shutdown for almost all third-octave bands below 80 Hz. Comparison between Figure 35 (a) and (b) and Figure 35 (c) and (d) reveals that the increased noise levels can also be observed for operational conditions selected based on matching wind speed conditions. This refutes the argument that the increased noise levels before and after shutdown can be attributed to differences in the wind conditions.

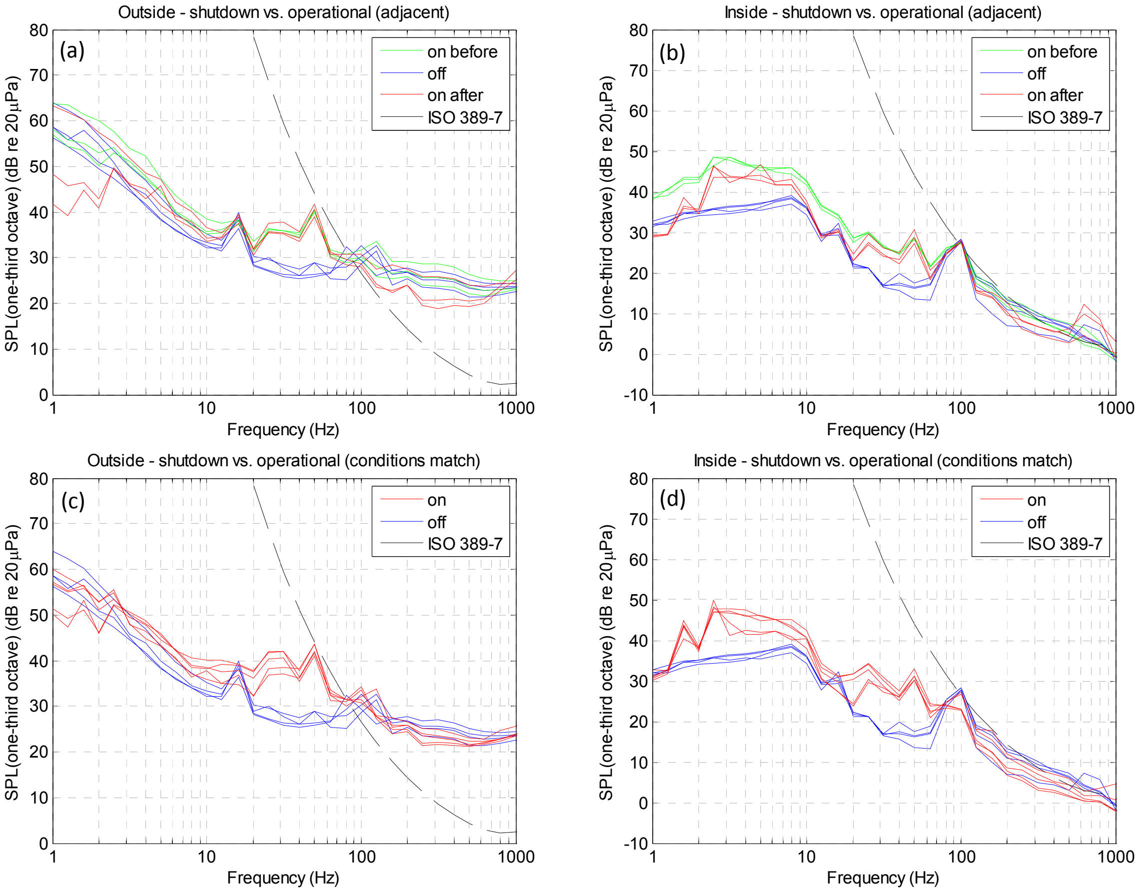


Figure 35 – Wind farm shutdown vs. operational 10th June, Fricker residence (SHUTDOWN 4).

The most significant difference in the spectra occurs for the 50 Hz third-octave band, where the sound pressure level difference between shutdown and operational cases can be higher than 15 dB for both outdoor and indoor measurements. The plots shown in Figure 35 indicate that the outdoor noise in the 50 Hz third-octave band is close to the audibility threshold for a person with normal hearing, which is defined in ISO 389-7 (2005). However, since wind turbine noise is highly variable with time, it is expected that peak noise levels would be higher than the 10-minute average levels. Hence, noise in the 50 Hz third-octave band is likely to be be audible outside and possibly inside to a person with normal hearing according to ISO 389-7 (2005).

The outdoor and indoor results shown in Figure 35 (a-d) also indicate that the sound pressure level in the 25 Hz and 31.5 Hz third-octave bands is higher when the wind farm is operating. Another characteristic that can be attributed to wind farm operation are the peaks in the infrasonic frequency range, which appear to correspond to harmonics of the blade-pass frequency. These peaks are more noticeable indoors where the contribution from wind-induced noise would be expected to be much lower.

Since the nearest wind turbine is located in the direction of 268° from the East 2 residence, it can be seen that the residence was downwind from the wind farm for all of the measurements according to Table 10. The wind speed measured at a height of 1.5 m in the vicinity of the residence was relatively low and did not exceed 2 m/s. The wind speed at hub height was above the cut-in speed of 3.5 m/s (Vestas, n.d.) but was lower than the rated speed of 15 m/s (Vestas, n.d.). Hence, due to the low hub height wind speeds, the sound pressure levels plotted in Figure 34 would be much lower than the maximum levels that would occur at this residence.

Table 10 – Wind conditions for shutdown vs. operational, 10th June, Fricker residence (SHUTDOWN 4).

	wind speed @1.5 m (m/s)	wind dir @1.5 m (°)	wind speed @10m (m/s)	wind dir @10 m (°)	wind speed @hub (m/s)	wind dir @hub (°)
SHUTDOWN						
min	1.1	168.8	3.1	281.3	9.8	306.0
max	1.3	337.5	4.3	326.3	10.5	308.0
ADJACENT						
min	0.2	247.5	1.3	270.0	8.7	303.5
max	2.0	292.5	4.1	303.8	12.8	307.2
CONDITIONS MATCH						
min	1.1	292.5	2.2	292.5	9.4	295.2
max	1.3	315.0	3.8	315.0	10.9	306.5

Overall levels were calculated from 10-minute data samples, which were weighted using the weightings discussed in Section 3. The outdoor results are shown in Table 11 and the indoor results are shown in Table 12. In general, the levels measured during wind farm operation were slightly higher than those measured when the wind farm was shutdown regardless of the applied weighting function. The small differences between shutdown and operational conditions could be explained by the low hub height wind speeds associated with the shutdown period. Nevertheless, a potential low-frequency noise issue is indicated by the maximum indoor value of $L_{Ceq} - L_{Aeq}$, which is higher than the recommended value of 20 dB when the wind farm is operating.

Table 11 – Outdoor acoustic descriptors for shutdown vs. operational, 10th June, Fricker residence (SHUTDOWN 4).

	L_{Ceq}	L_{Geq}	L_{Ceq}- L_{Aeq}
SHUTDOWN			
min	40.9	46.1	2.3
max	45.9	48.8	6.3
ADJACENT			
min	41.1	48.3	3.4
max	45.6	50.4	8.1
CONDITIONS MATCH			
min	45.6	47.6	5.3
max	47.5	52.6	9.4

Table 12 – Indoor acoustic descriptors for shutdown vs. operational, 10th June, Fricker residence (SHUTDOWN 4).

	L_{Aeq}	L_{A90}	L_{Ceq}	L_{Geq}	L_{Ceq}- L_{Aeq}	$L_{pA,lf}$	DEFRA
SHUTDOWN							
min	14.5	12.8	32.0	42.2	17.5	6.1	100.0
max	15.5	13.9	33.1	42.9	17.9	7.1	100.0
ADJACENT							
min	14.4	12.6	34.7	44.1	17.8	7.3	100.0
max	16.9	13.5	37.4	49.1	22.5	7.6	100.0
CONDITIONS MATCH							
min	12.5	11.5	35.8	44.3	19.2	5.3	100.0
max	16.6	13.4	38.4	48.6	24.9	7.4	100.0

5.5 Shutdown 6 – West site

The unweighted 10-minute averaged third-octave spectra for the shutdown and operational cases are shown in Figure 36 (a-d). The outdoor and indoor noise levels measured during the shutdown cases were consistently lower than those measured when the wind farm was operating for the majority of third-octave bands between 1 Hz and 1000 Hz. Comparison between Figure 36 (a) and (b) and Figure 36 (c) and (d) reveals that the increased noise levels can also be observed for operational conditions selected on the basis of matching wind speed conditions. This refutes the argument that the increased noise levels before and after shutdown can be attributed to differences in the wind conditions.

The peak in the 100 Hz third-octave band is most likely attributable to the substation, which is located nearby the residence and this explains why the peak was present when the wind farm was shutdown. Nevertheless, it can be seen in Figure 36 (a) and (c) that there may also have been a contribution from the wind farm to this third-octave band.

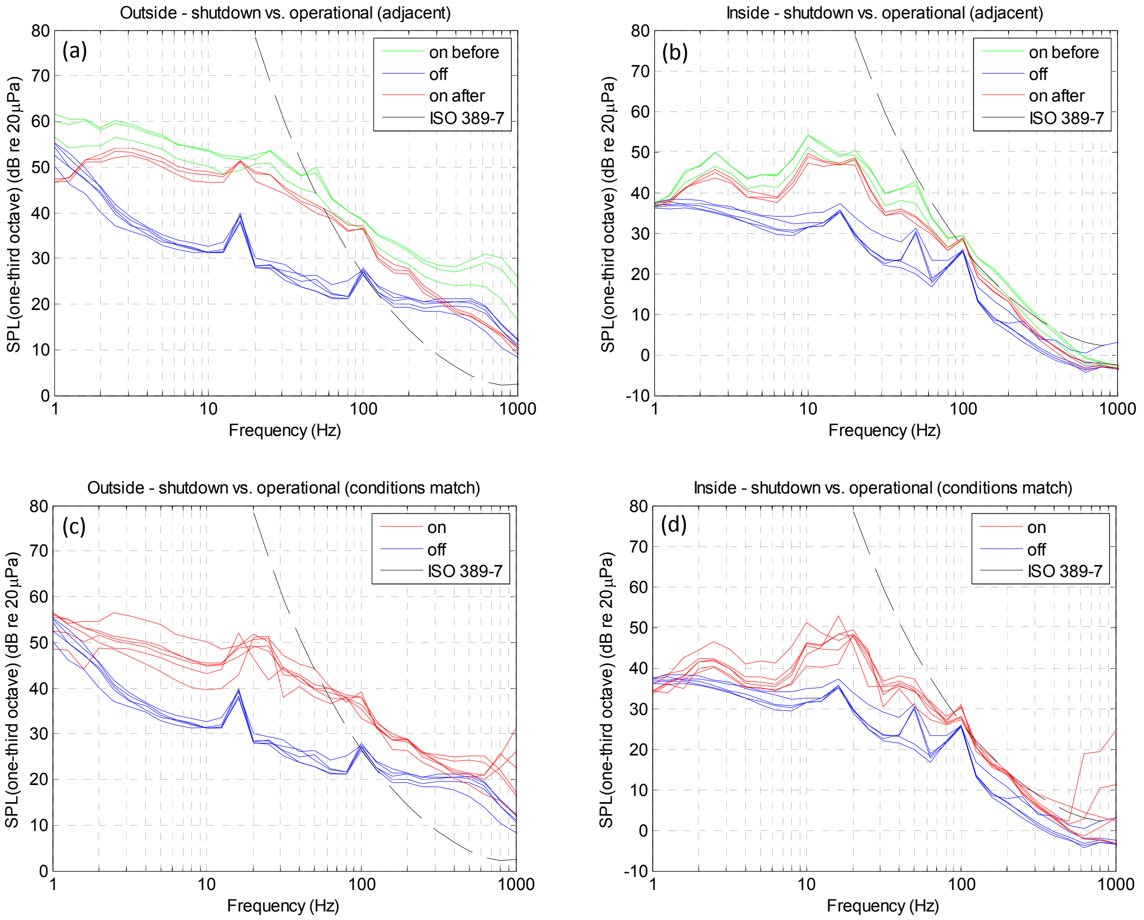


Figure 36 – Wind farm shutdown vs. operational 14th June, Quast residence (SHUTDOWN 6).

The most significant difference in the spectra occurs for the 50 Hz third-octave band, where the sound pressure level difference between shutdown and operational cases can be higher than 25 dB for the outdoor measurements. The difference does not appear to be so significant for the indoor results, since there is a peak in the 50 Hz third-octave band corresponding to the period during which the wind farm was shutdown. It is believed that the peak in this third-octave band when the wind farm is shut down can be attributed to compressor noise from a refrigerator which was located in the kitchen of this residence. A narrowband analysis with 0.1 Hz resolution shown in Figure 37 shows that the peak close to 50 Hz is highly tonal. This peak is present both when the wind farm is operational and when it is shutdown but it varies slightly in frequency between the two cases. The fact that the tonal peak close to 50 Hz is present for one measurement during the shutdown and absent for another provides further evidence that the noise source is the refrigerator compressor. The narrowband plot shown in Figure 37 also reveals a broadband hump when the wind farm is operational but not when the wind farm is shut down. This hump is centred around 46 Hz; thus it contributes to increased levels in the 50 Hz third-octave band.

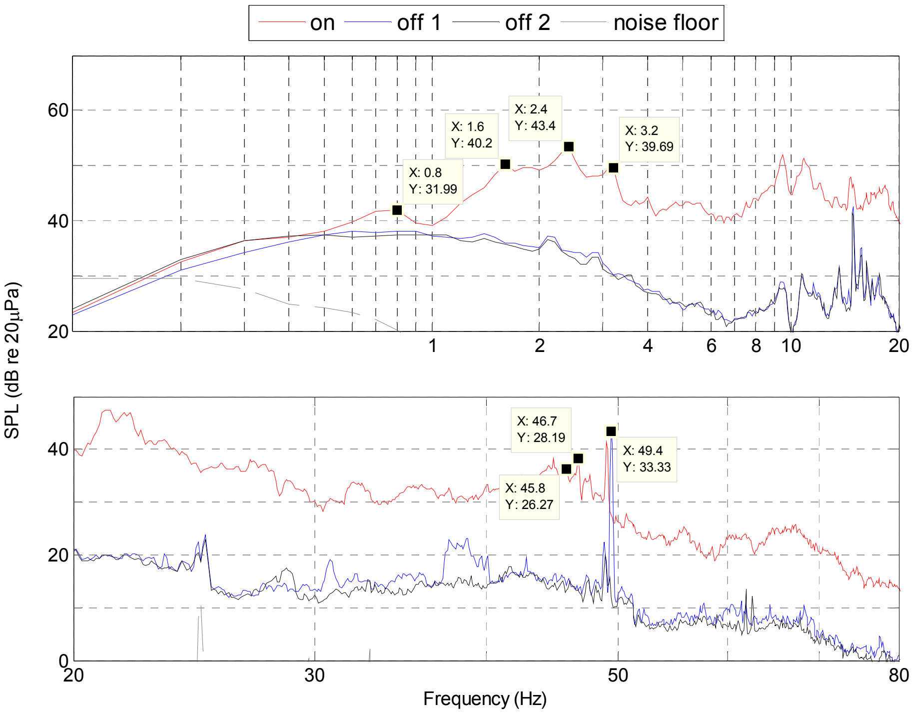


Figure 37 – Comparison between narrowband results for shutdown vs. operational conditions (SHUTDOWN 6).

The difference between the shutdown and operational cases for the outdoor results for the 50 Hz third-octave band is over 10 dB higher than that which was shown in the EPA report (2013), where the maximum difference was around 14 dB. For some reason, the noise measured by the EPA in the 50 Hz third-octave band during shutdown was significantly higher than the measurements taken at the same time in this study. This could be related to microphone positioning since the EPA microphone was close to the house and several obstacles which may have contributed to noise in the 50 Hz third-octave band. The unweighted third-octave indoor levels were not reported by the EPA for Shutdown 6. The plots shown in Figure 36 (a) indicate that for some measurements, the noise in the 50 Hz third-octave band exceeds the audibility threshold outdoors for a person with normal hearing, which is defined in ISO 389-7 (2005). The indoor results shown in Figure 36 (b) indicate that the noise level in the 50 Hz third-octave band is close to the audibility threshold for some measurements and the supposed compressor noise is low enough for these cases that it would have a negligible influence on the third-octave band results. The high variability associated wind turbine noise is expected to give rise to higher peak noise levels compared to the 10-minute average levels. Hence, noise in the 50 Hz third-octave band is likely to be audible both outside and inside to a person with normal hearing according to ISO 389-7 (2005).

The indoor results shown in Figure 36 (b) and (c) indicate that peaks in the spectra occurred at 1.6 Hz, 10 Hz and 20 Hz when the wind farm was operational but these peaks were not evident when the wind farm was shutdown. In general, the level of infrasound was higher when the wind farm was operational and peaks in the spectra are evident below 20 Hz when the wind farm is operational. These peaks are slightly more noticeable indoors where the contribution from wind-induced noise would be expected to be much lower. It can be seen in the narrowband plot in Figure 37 that these peaks correspond to the blade-pass frequency and harmonics. On the other hand, when the wind farm is shutdown, the infrasound is more broadband in nature and the only significant low frequency peak occurs at 16 Hz, which is most likely a structural resonance of the residence. It has been found that structural resonances occur in the range of 12-30 Hz, according to data measured for several different housing structures (Hubbard, 1982).

Given that nearest wind turbine is located in the direction of 98° from the residence, it can be seen that the residence was not downwind from the wind farm for any of the measurements according to Table 13. The wind speed measured at a height of 1.5 m in the vicinity of the residence was relatively low and did not exceed 1.3 m/s. This in contradiction with the results presented in the EPA report (EPA, 2013), where the wind speed at 4 m was reported as 2 m/s. This is even higher than the wind speed that was measured at a height of 10 m in the present study and is unlikely since the hub height wind speeds at the time were relatively low as shown in Table 13 and confirmed by results presented in the EPA report (EPA, 2013). The wind speed at hub height was above the cut-in speed of 3.5 m/s (Vestas, n.d.) but was at least 5 m/s lower than the rated speed of 15 m/s (Vestas, n.d.). Hence, due to the lack of downwind conditions as well as low hub height wind speeds, the sound pressure levels plotted in Figure 36 would be much lower than the maximum levels that would occur at this residence.

Table 13 – Wind conditions for shutdown vs. operational, 14th June, Quast residence (SHUTDOWN 6).

SHUTDOWN						
	wind speed @1.5 m (m/s)	wind dir @1.5 m (°)	wind speed @10m (m/s)	wind dir @10 m (°)	wind speed @hub (m/s)	wind dir @hub (°)
min	0.9	157.5	0.9	180.0	6.0	180.9
max	0.9	157.5	1.1	180.0	6.7	185.2
ADJACENT						
min	0.2	135.0	0.2	180.0	4.6	166.9
max	1.3	157.5	1.6	180.0	7.8	185.6
CONDITIONS MATCH						
min	0.9	146.3	0.4	157.5	5.7	159.1
max	0.9	191.3	1.3	202.5	6.9	174.1

Overall levels were calculated from 10-minute data samples, which were weighted using the weightings discussed in Section 3. The outdoor results are shown in Table 14 and the indoor results are shown in Table 15.

Table 14 – Outdoor acoustic descriptors for shutdown vs. operational, 14th June, Quast residence (SHUTDOWN 6).

SHUTDOWN				
	L_{Aeq}	L_{Ceq}	L_{Geq}	L_{Ceq}- L_{Aeq}
min	19.7	35.2	46.9	11.1
max	24.1	36.9	48.5	13.9
ADJACENT				
min	24.6	49.5	61.8	20.1
max	35.5	55.7	65.8	24.6
CONDITIONS MATCH				
min	26.0	49.7	61.0	5.7
max	46.5	52.4	63.2	23.6

In general, the levels measured during wind farm operation were higher than those measured when the wind farm was shutdown, regardless of the applied weighting function. The small differences between shutdown and operational conditions could be explained by the low hub height wind speeds associated with the shutdown period. Nevertheless, a potential low-frequency noise issue is indicated by the maximum indoor value of $L_{Ceq} - L_{Aeq}$, which is higher than the recommended value of 20 dB when the wind farm is operating. While this value was also exceeded when the wind farm was shutdown, the difference was still significantly higher when the wind farm was operational.

Table 15 – Indoor acoustic descriptors for shutdown vs. operational, 14th June, Quast residence (SHUTDOWN 6).

SHUTDOWN							
	L_{Aeq}	L_{A90}	L_{Ceq}	L_{Geq}	L_{Ceq}- L_{Aeq}	$L_{pA,lf}$	DEFRA
min	10.2	9.3	32.9	45.1	21.5	4.4	100.0
max	12.6	9.7	37.0	48.2	24.8	6.8	100.0
ADJACENT							
min	14.4	10.8	45.3	59.3	30.9	10.2	100.0
max	18.4	16.5	50.2	63.1	32.1	15.6	100.0
CONDITIONS MATCH							
min	14.7	10.8	45.6	58.6	14.3	9.6	100.0
max	32.1	14.8	47.5	61.8	31.9	12.4	100.0

6 Noise Diaries

The following analysis considers data that corresponds to instances where residents reported that they were annoyed by wind farm noise. Most of the times were selected based on information published in the EPA report but some additional times were also included which were specific to complaints registered by the resident hosting the instrumentation. Three of the locations in this report were not part of the EPA study and in two of these cases (East 2 and Southwest), the noise diaries completed by the resident hosting the instrumentation were consulted exclusively. For the Township 2 residence, the township noise diaries were considered to be the most relevant record of complaints. In all cases, the audio files containing extraneous noise sources such as vehicle and animal noise were eliminated. In some cases, the indoor results had to be discarded due to contamination from speech and indoor appliances. Often, the corresponding outdoor measurements were still valid and thus, the number of outdoor plots exceeds the number of indoor plots for some locations.

6.1 Third-octave Spectra

The third-octave unweighted spectra provide an excellent overview of the general trends in the results for the various times at which complaints were recorded. On the other hand, it is not possible to see details such as tonal peaks and sidebands related to amplitude modulation due to the low-frequency resolution associated with a third-octave analysis. Hence, narrow-band plots are presented in Section 6.2.

The third-octave plots for the residences described in Section 4 are presented in Figure 38 to Figure 45. The results recorded during the daytime are shown in red and those recorded during the night-time hours of 12 am – 5 am are shown in blue. The plots indicate that the peak in the 50 Hz third-octave band which was identified in Section 5 as being associated with wind farm operation is a consistent feature of the noise diary results. This peak is more than 15 dB higher than the level in the adjacent third-octave band of 63 Hz. According to standards such as NZS 6808:2010 (2010) and ANSI S12.9 - Part 4 (2005), this would be classified as a tone and hence an adjustment to the allowable wind farm noise limits would be required. In addition, a significant number of plots show that the noise in the 50 Hz third-octave band exceeds the audibility threshold (ISO 389-7, 2005) by up to 15 dB for the outdoor results and by up to 5 dB for the indoor results. It is interesting to note that the noise in the 50 Hz third-octave band even exceeds the audibility threshold (ISO 389-7, 2005) at a distance of 8.7 km from the wind farm as shown in Figure 44. This highlights the fact that low-frequency noise can propagate over large distances due to poor absorption from the atmosphere and ground (Leventhall, 2003).

Peaks in the infrasonic range are also consistently evident in the results, particularly for the indoor results where there is minimal contamination from wind-induced noise. The peaks occur for the majority of the results in the 1.6 Hz and 2.5 Hz third-octave bands, which correspond to the 2nd and 3rd harmonic of the blade-pass frequency of 0.8 Hz. This blade-pass frequency is calculated based on the nominal rotational speed of 16.1rpm for a Vesta V90-3 MW wind turbine (Vestas, n.d.). Further peaks are evident in some of the results, particularly those measured indoors, as shown in Figure 42 (b) and Figure 43 (b).

Low-frequency peaks also occur in the 25 Hz and 31.5 Hz third-octave bands but these peaks are most significant outdoors at most locations. An exception to this is the Southwest residence for which one of the room resonances was 28 Hz, corresponding to a room dimension of 6.2 m. Compared to rooms in other residences in which measurements were taken, this room was relatively large. The higher peaks in the indoor spectrum for this residence are shown in Figure 45 (b).

In summary, the results presented in Figure 38 to Figure 45 indicate that a significant number of diary entries were recorded at times when there are significant peaks in the spectra. The most significant of these peaks corresponds to the 50 Hz third-octave band where the noise level is often above the audibility threshold (ISO 389-7, 2005) and can also be classified as a tone according to some standards (NZS 6808:2010, 2010; ANSI S12.9 - Part 4, 2005).

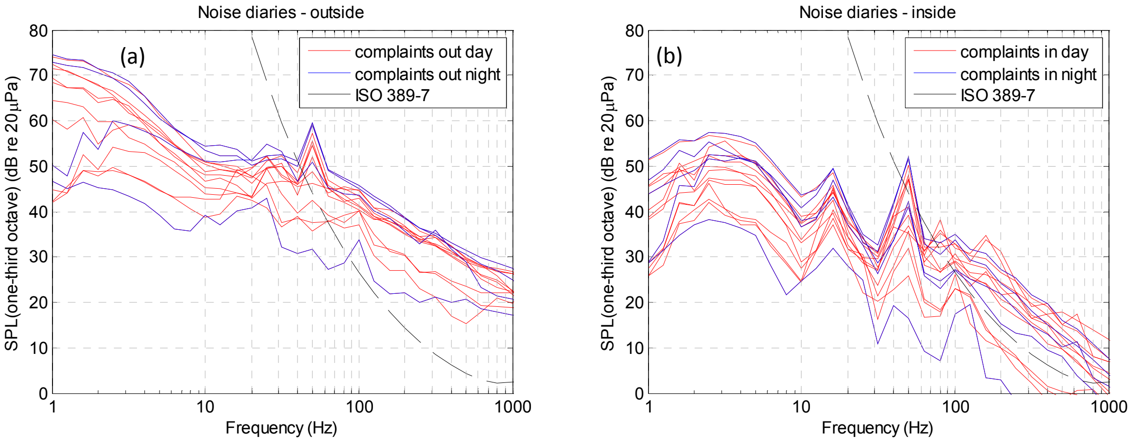


Figure 38 – Noise diaries, Township site 1.

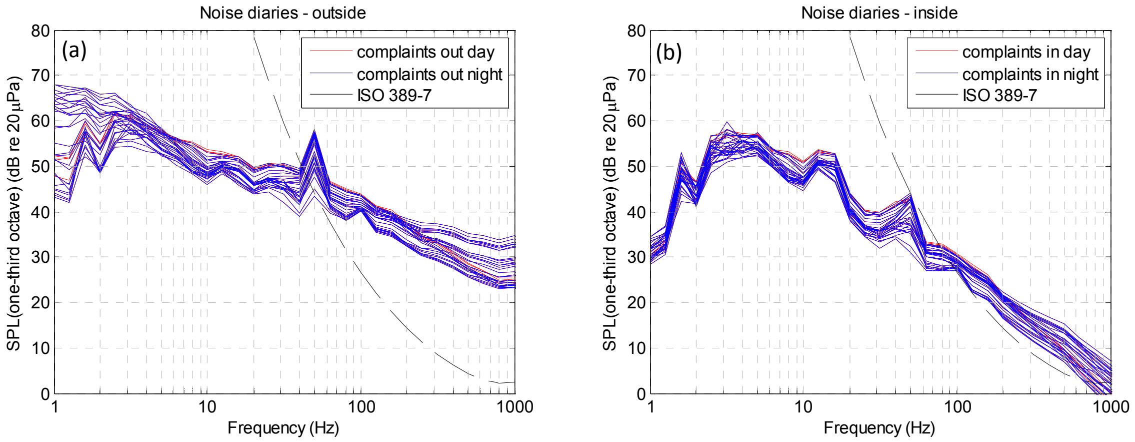


Figure 39 – Noise diaries, Township site 2.

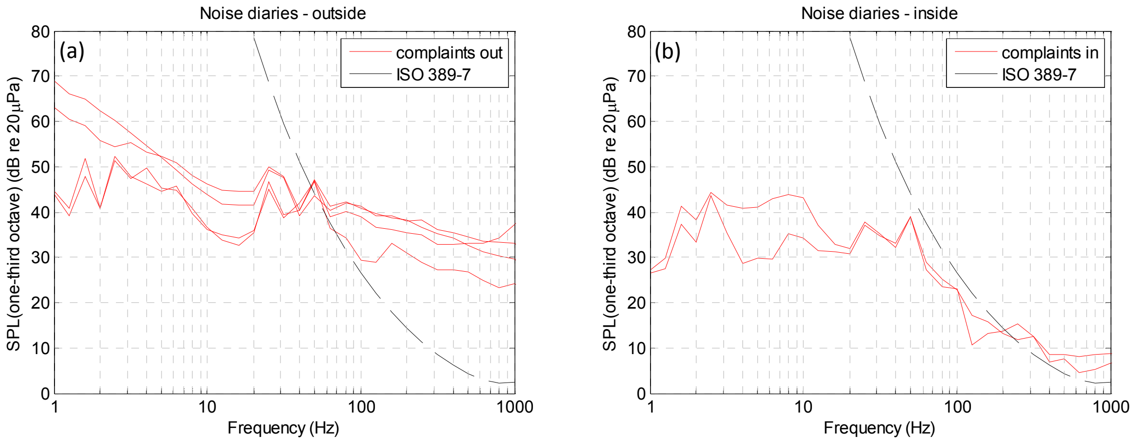


Figure 40 – Noise diaries, North site.

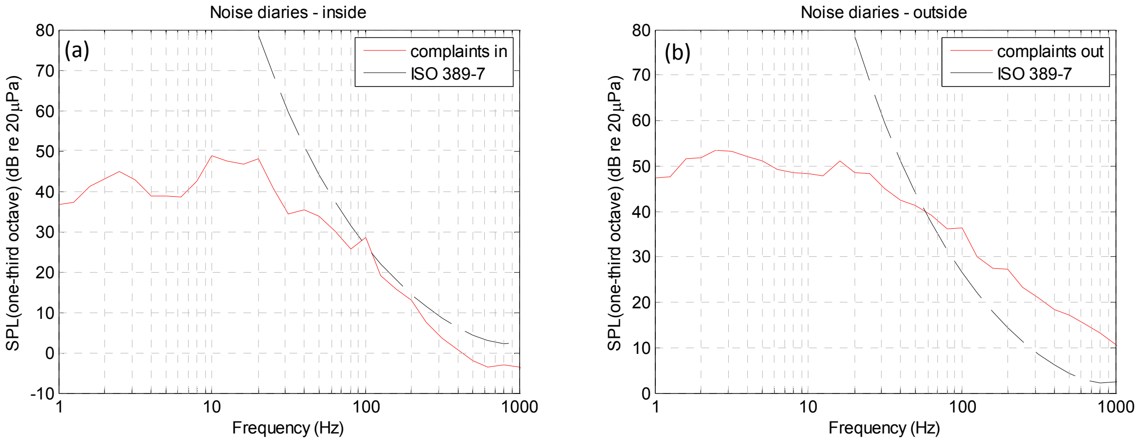


Figure 41 – Noise diaries, West site.

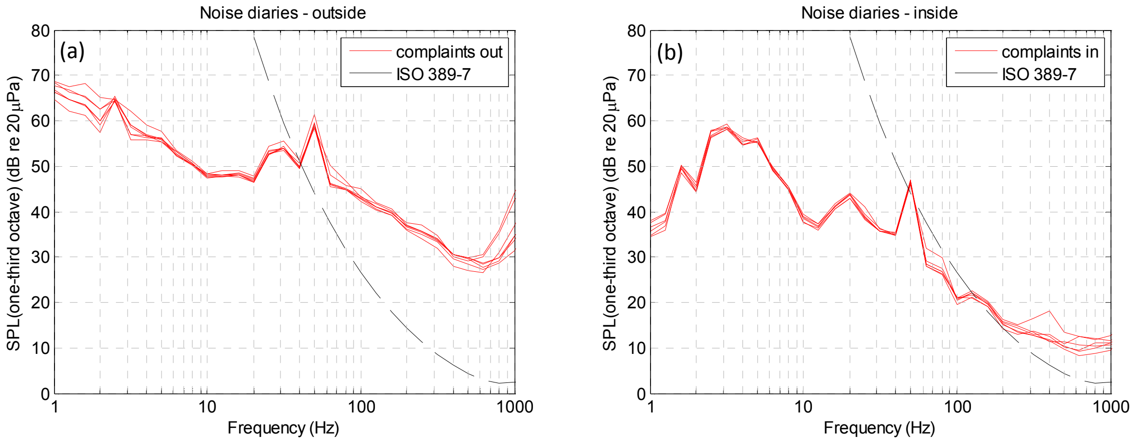


Figure 42 – Noise diaries, South East site.

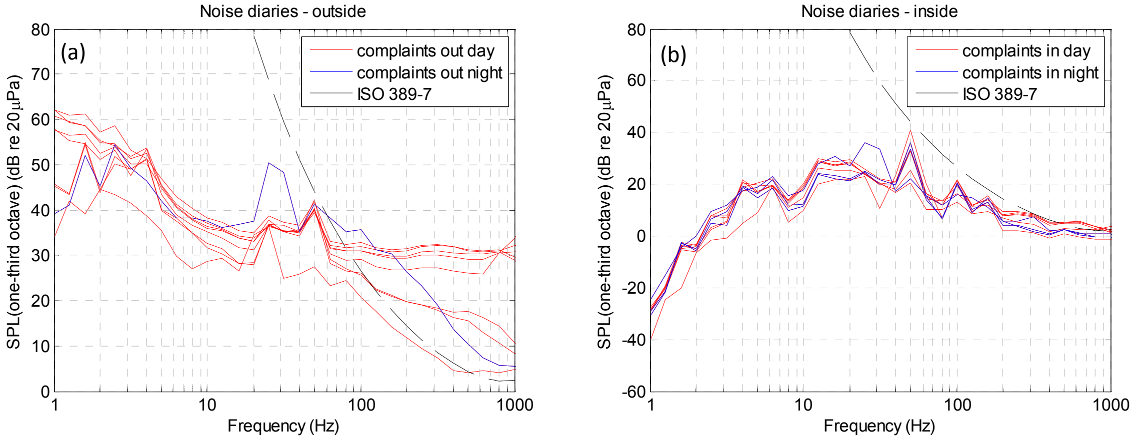


Figure 43 – Noise diaries, East site.

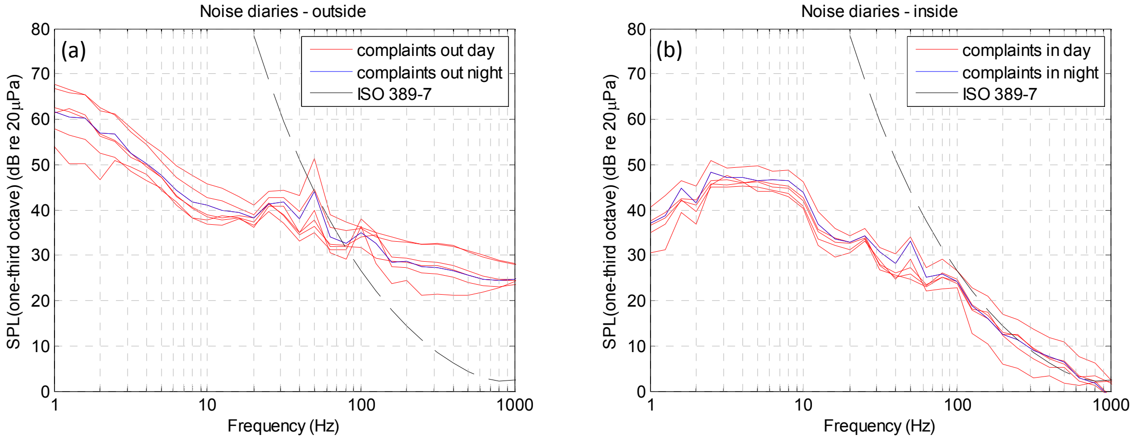


Figure 44 – Noise diaries, East 2 site.

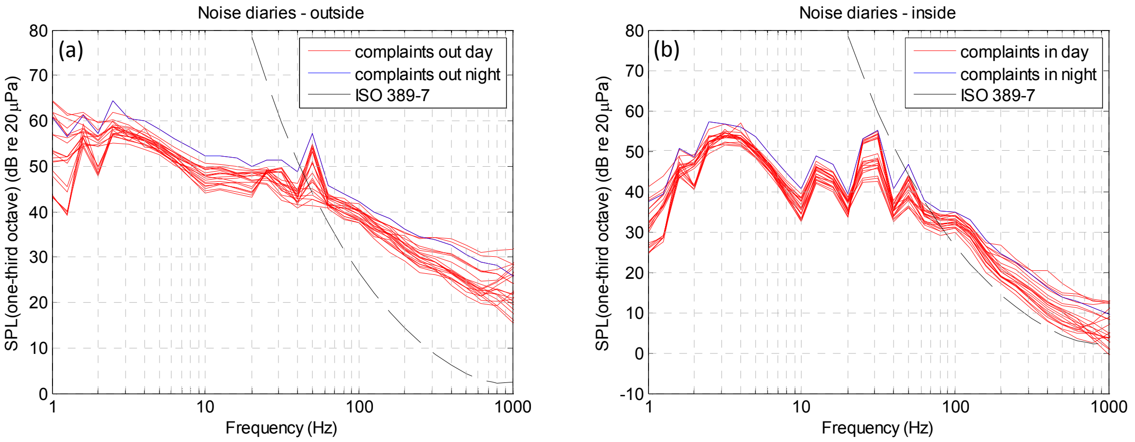


Figure 45 – Noise diaries, South West site.

6.2 Narrow-band analysis

As mentioned in the previous section, a narrow-band analysis with a fine resolution can provide more detail about the tonal components of the noise source as well as sidebands associated with amplitude modulation. A frequency resolution of 0.1 Hz was chosen to ensure that peaks spaced at 0.8 Hz, the blade-pass frequency, would be resolved accurately. The narrow-band plots have been divided into two frequency ranges to improve resolution. Noise diary entries from a range of locations were selected based on the clarity of the blade-pass frequency and harmonics as well as the instance of tonal peaks with side-bands spaced at the blade-pass frequency. Although the EPA specified a start time and end time in their noise diary record sheet, it is believed that the 10-minute measurement before a given complaint could also prove useful as it may have taken some time for an individual to register their annoyance. Hence, some measurements were chosen based on this rationale.

The outdoor and indoor narrow-band plots are shown in Figure 46 to Figure 53 for the residences described in Section 4. The plots corresponding to the outdoor measurements reveal that the blade-pass frequency (0.8 Hz) and harmonics can be clearly identified and the results are consistently recorded by at least three different microphones with different wind shields in different positions. The magnitude of the peaks can be up to 20 dB above the levels in adjacent frequency bins as shown in Figure 48. Another consistent feature of the outdoor results recorded at different residences is the presence of tones, which occur at 23 Hz, 28 Hz, 46 Hz, 56 Hz and 69 Hz. It can be seen that the first two of these tonal frequencies (23 Hz and 28 Hz) appear to be the fundamental frequencies and the other peaks appear to be harmonics. The majority of these peaks have sidebands, which are spaced at the blade-pass frequency of 0.8 Hz. The sidebands are indicative of amplitude modulation occurring at the blade-pass frequency. It is also possible that the existence of the peaks and sidebands is related to selective amplification of harmonics of the blade-pass frequency. This theory is quite plausible since it has been found that with a resolution of 0.0017 (the maximum possible for a 10-minute sample with sampling frequency of 10,240 Hz), each peak is an exact multiple of the blade-pass frequency. There is good agreement between the results obtained using microphones with various secondary windshields, which were separated by several metres.

The indoor results were recorded with three different microphones located at varying positions around the room. The data presented below 6 Hz is uncalibrated and hence does not reflect the true sound pressure level for these frequencies. However, peaks at the blade-pass frequency and harmonics indicate that the microphones are still capable of measuring (albeit with decreased accuracy) below 6 Hz. At all residences, one microphone was located in a room corner as this is the position of the antinode for all room resonances and as such, the associated sound pressure level is expected to be highest.

Several aspects of the indoor results are similar to the outdoor results, including peaks at the blade-pass frequency harmonics as well as the peaks at 23 Hz, 28 Hz, 46 Hz, 56 Hz and 69 Hz mentioned previously with their associated sidebands spaced at the blade-pass frequency. The peaks at 23 Hz, 28 Hz and 46 Hz are consistently present in all indoor plots whereas the higher frequency peaks are not visible for some locations.

In the infrasonic range, below 20 Hz, there is good agreement between results measured with microphones in different positions, since the associated wavelengths are very large relative to the room dimensions and thus standing waves (room resonances) do not occur. On the other hand, there is a large variation in the sound pressure level with room location for frequencies between 20 Hz and 100 Hz as this is the frequency range where room resonances would be expected to exist. The change in sound pressure level with room location could cause annoyance in the situation where the noise was audible and the occupant was moving around the room. Resonance effects could also increase the sound pressure level at selective frequencies, as can be seen most clearly in Figure 55 at 28 Hz.

Overall, the narrow-band results indicate that several low-frequency tones are present in both the indoor and outdoor results and it appears that significant amplitude modulation is occurring at the blade-pass frequency. As shown in Section 6.1, both outdoor and indoor noise in the 50 Hz third-octave band measured in the vicinity of the Waterloo wind farm can be audible to a person with normal hearing according to ISO 389-7 (2005). Moreover, it is possible that low-frequency noise and infrasound can affect the body regardless of whether or not it is classified as audible (Salt, 2014; Dooley, 2013).

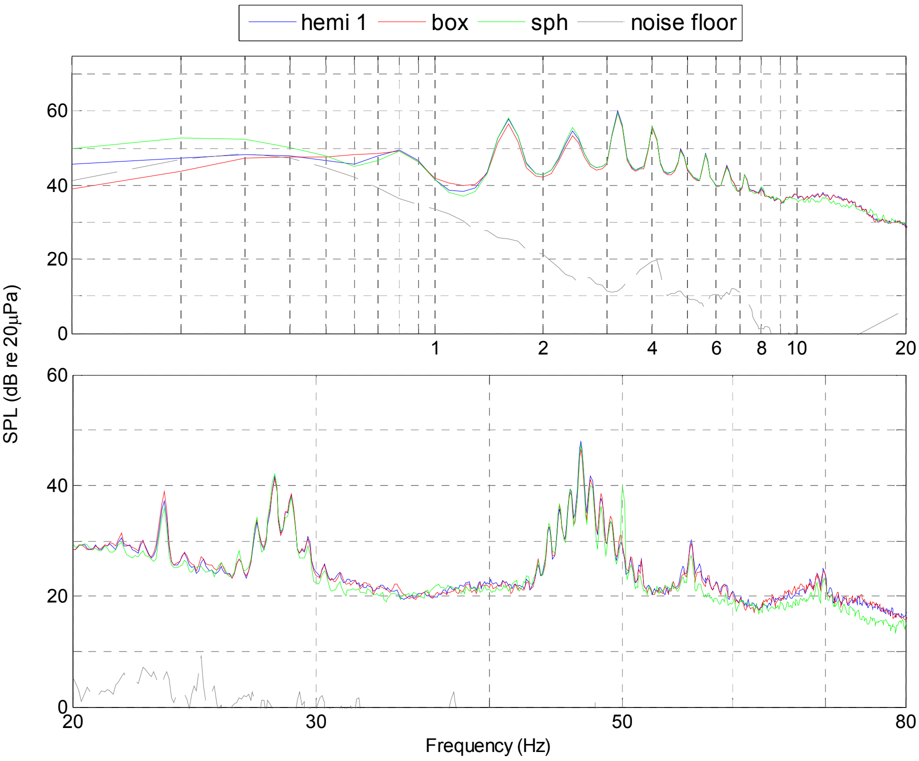


Figure 46 – Noise diary entry, outside results, 12th April, 3:35 – 3:45, Township 2 site.

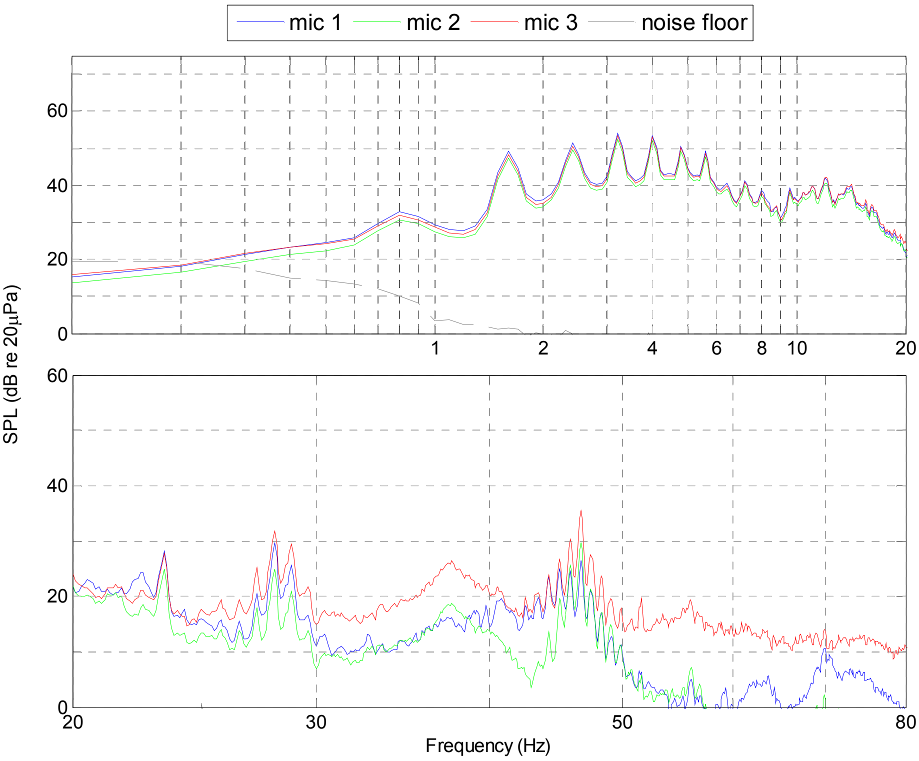


Figure 47 – Noise diary entry, inside results, 12th April, 3:35 – 3:45, Township 2 site.

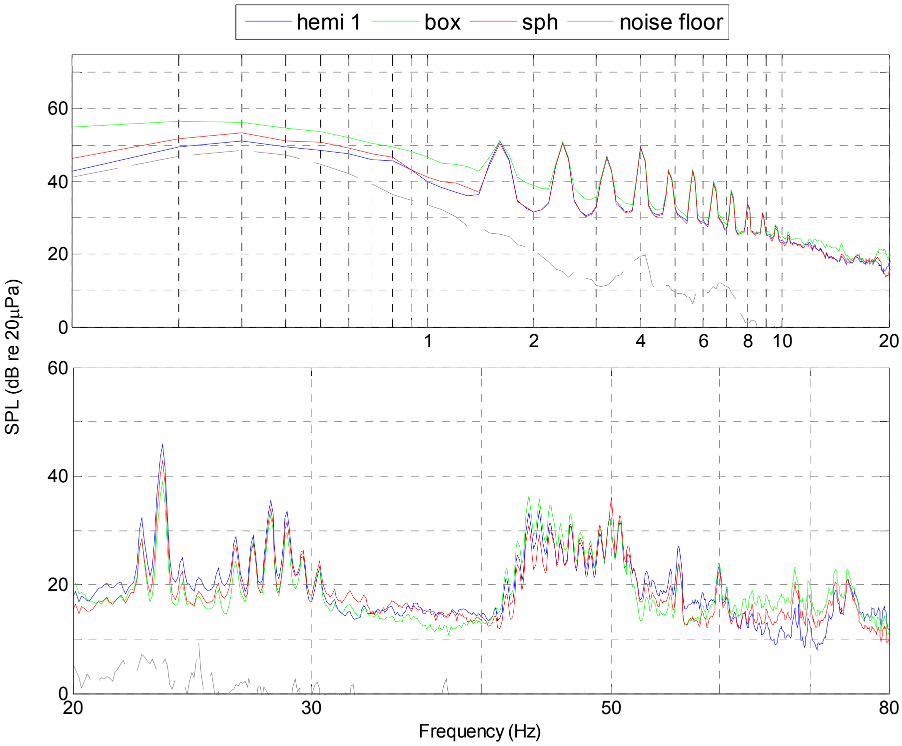


Figure 48 – Noise diary entry, outside results, 21st April, 22:24 – 22:34, North site.

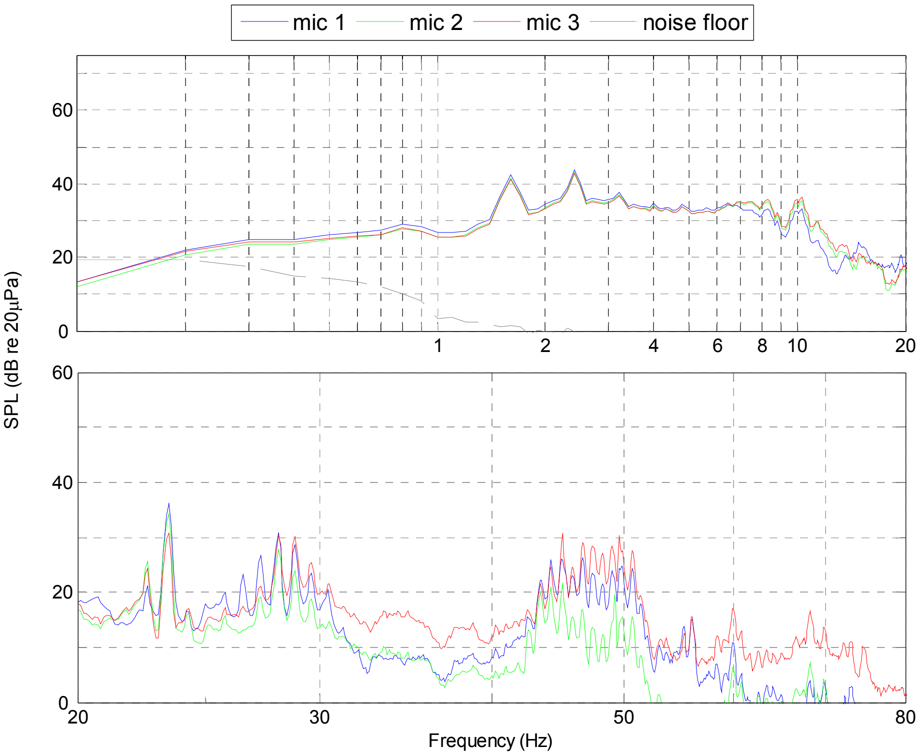


Figure 49 – Noise diary entry, inside results, 21st April, 22:24 – 22:34, North site.

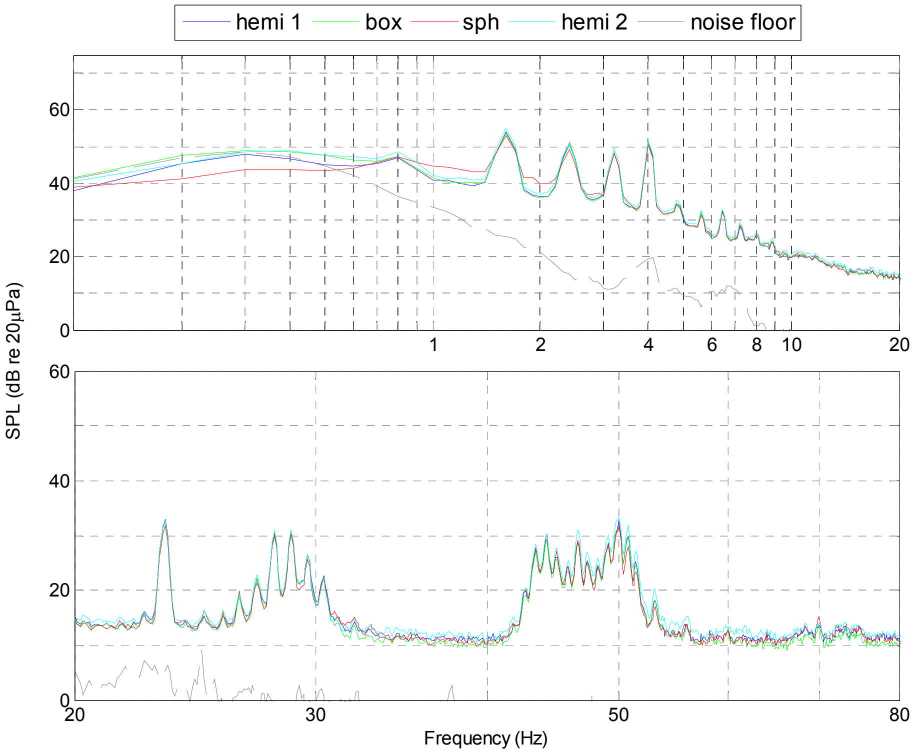


Figure 50 – Noise diary entry, outside results, 27th April, 4:33 – 4:43, East site.

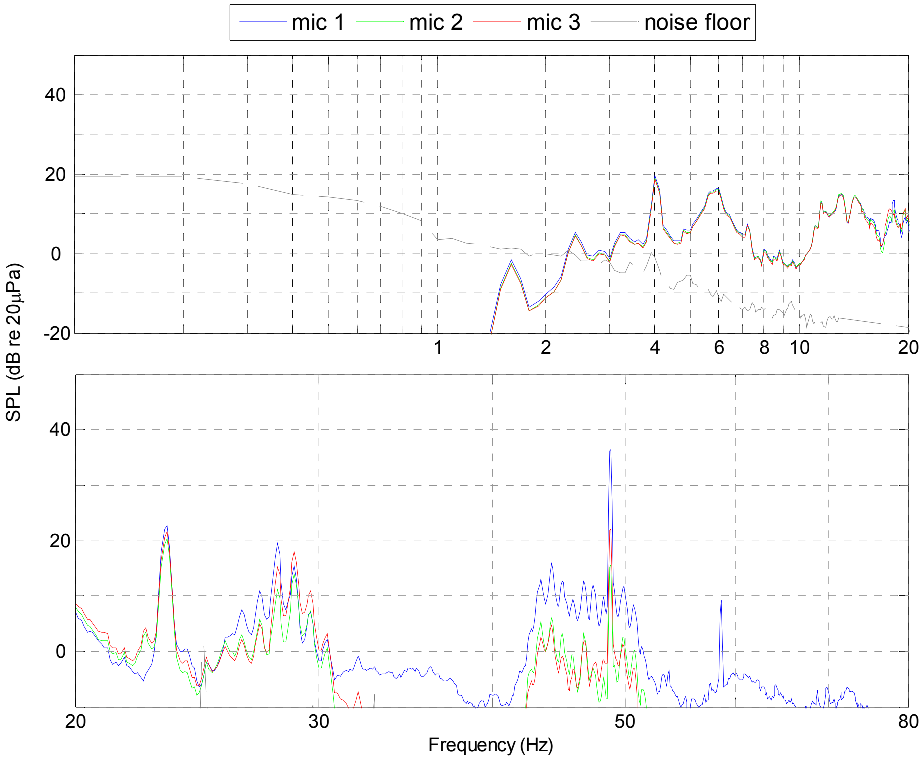


Figure 51 – Noise diary entry, inside results, 27th April, 4:33 – 4:43, East site.

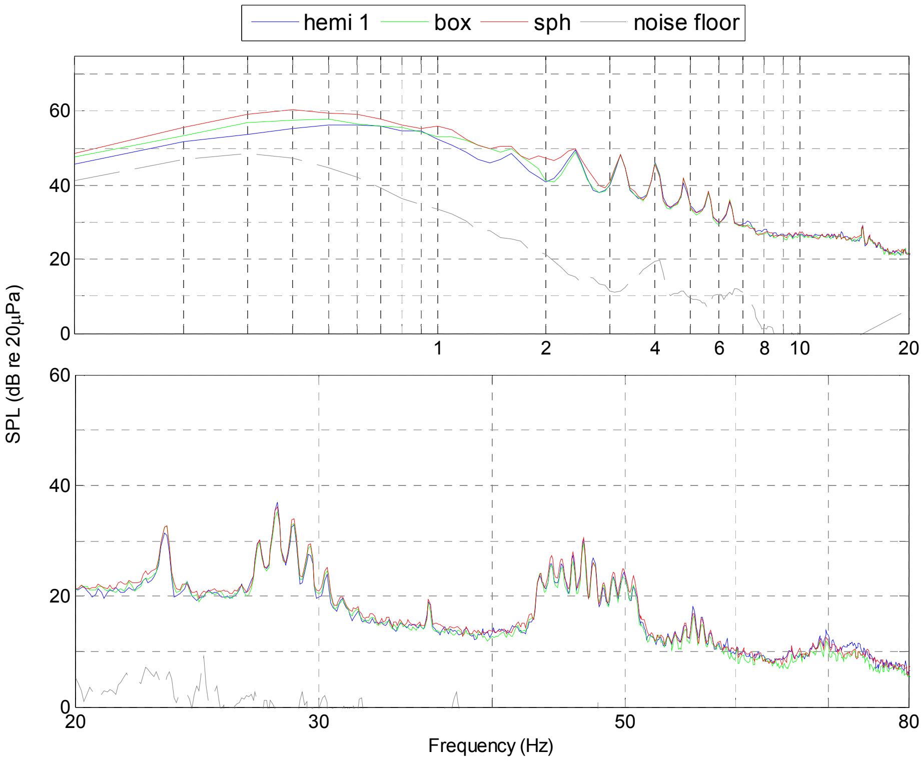


Figure 52 – Noise diary entry, outside results, 5th June, 22:00 – 22:10, East site 2.

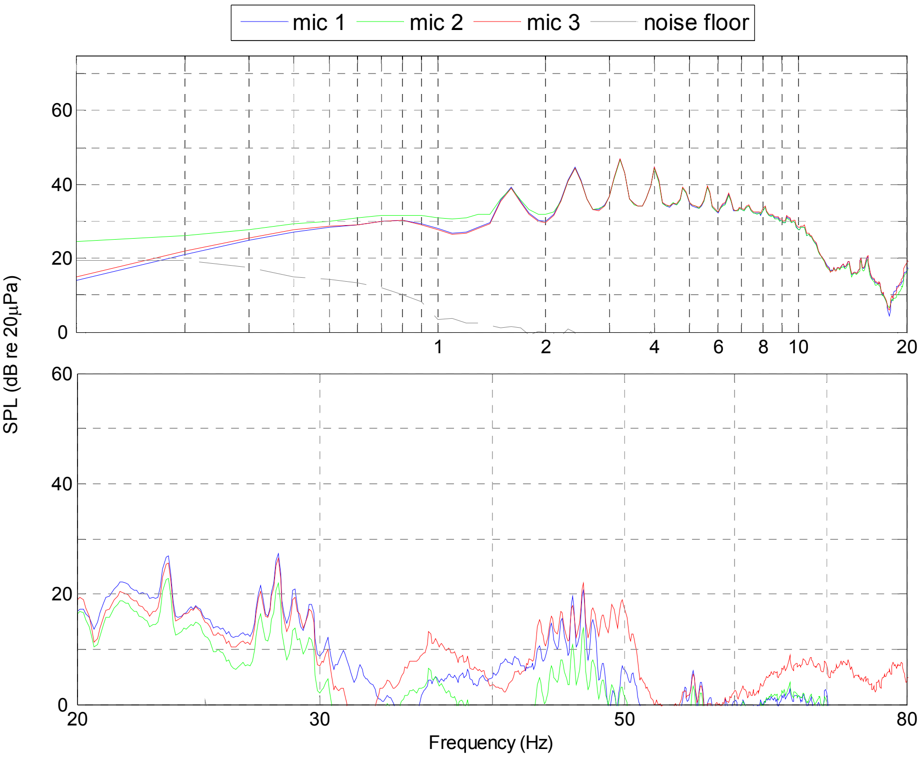


Figure 53 – Noise diary entry, inside results, 5th June, 22:00 – 22:10, East site 2.

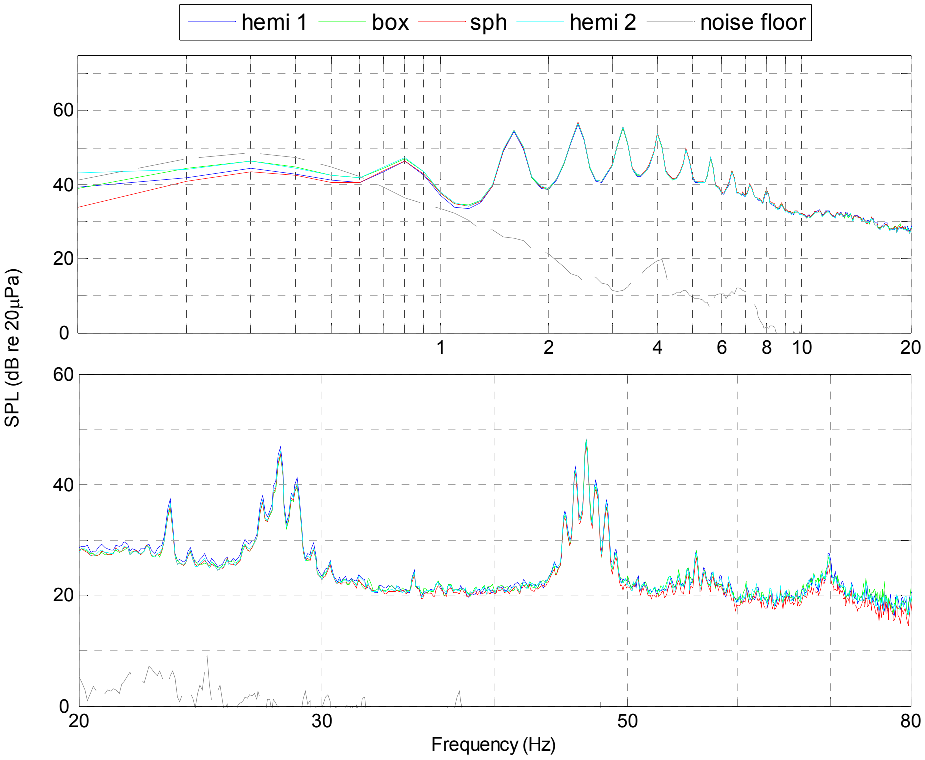


Figure 54 – Noise diary entry, outside results, 8th May, 18:02 – 18:12, South West site.

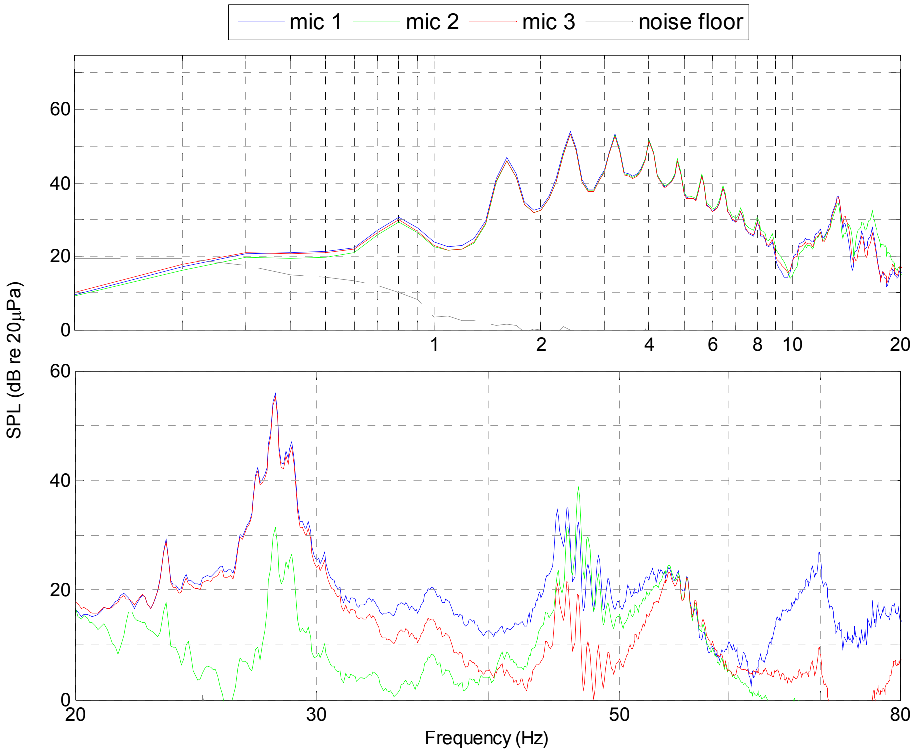


Figure 55 – Noise diary entry, inside results, 8th May, 18:02 – 18:12, South West site.

7 Noise Incidents Exceeding 40 dB(A)

A large number of data points were found to exceed the allowable limit of 40 dB(A). According to the current SA EPA guidelines (EPA, 2009), this would not necessarily lead to non-compliance of the wind farm as this is determined by the regression fit applied to 2,000 or more data points. On the other hand, if the wind farm was in fact responsible for the noise levels exceeding 40 dB(A) between the hours of 12 am and 5 am, it does call into question the appropriateness of the guidelines. Hence, the aim of this section is to show the unweighted and A-weighted third-octave spectra for measurements where the noise level was greater than 40 dB(A). The shape of the spectrum highlights the relative contribution of the third-octave frequencies, shedding light on whether or not the wind farm is the main contributing factor. For comparison, measurements for which the A-weighted noise level was significantly lower are also plotted. Data with obvious noise contamination has been removed from this analysis.

In general, the results shown in Figure 56 to Figure 59 indicate that there are fewer peaks when the outdoor noise level is greater than 40 dB(A) than when it is less than 40 dB(A). On the other hand, the peak in the 50 Hz third-octave band is much more significant and at the same time, the level of broadband noise is higher across the entire frequency spectrum. The noise level in the 50 Hz third-octave band would be audible both indoors and outdoors to a person with normal hearing according to ISO 389-7 (2005). In addition, the peak in the 50 Hz third-octave band is more than 15 dB higher than the level in at least one of the adjacent third-octave bands for the outdoor and indoor results for the Township location shown in Figure 56 (a) and (b). According to standards such as NZS 6808:2010 (2010) and ANSI S12.9 - Part 4 (2005), this would be classified as a tone and hence an adjustment to the allowable wind farm noise limits would be required.

Observation of the spectra corresponding to low overall noise levels reveals that there is still evidence of wind turbine noise in the form of peaks at the blade-pass frequency and its harmonics and these are most evident in Figure 56 (a), Figure 57 (a) and Figure 59 (a). The peak at 50 Hz is also present in many of the spectra but the level is much lower than the peak associated with overall noise levels exceeding 40 dB(A). The most distinct example of this is shown in Figure 56 (b) where the indoor noise level in the 50 Hz third-octave band varies by more than 35 dB over the measurement period.

Comparison between the levels of infrasound associated with the high and low overall A-weighted noise levels indicates that the levels are consistently higher when the outdoor noise level is greater than 40 dB(A). The high-level noise spectra also contain fewer peaks in the infrasonic range and the increase in noise level with decreasing frequency is also greater below 10 Hz. These spectral characteristics suggest the presence of wind-induced noise.

In summary, this analysis shows that the peak in the 50 Hz third-octave band is significantly higher when the overall A-weighted noise levels exceed 40 dB(A). This indicates the presence of wind turbine noise, as was discussed in Section 5. There is also a significant increase in the levels of broadband noise across the spectrum from 1 Hz to 1000 Hz. This increase can be attributed to both wind turbine noise and wind-induced noise.

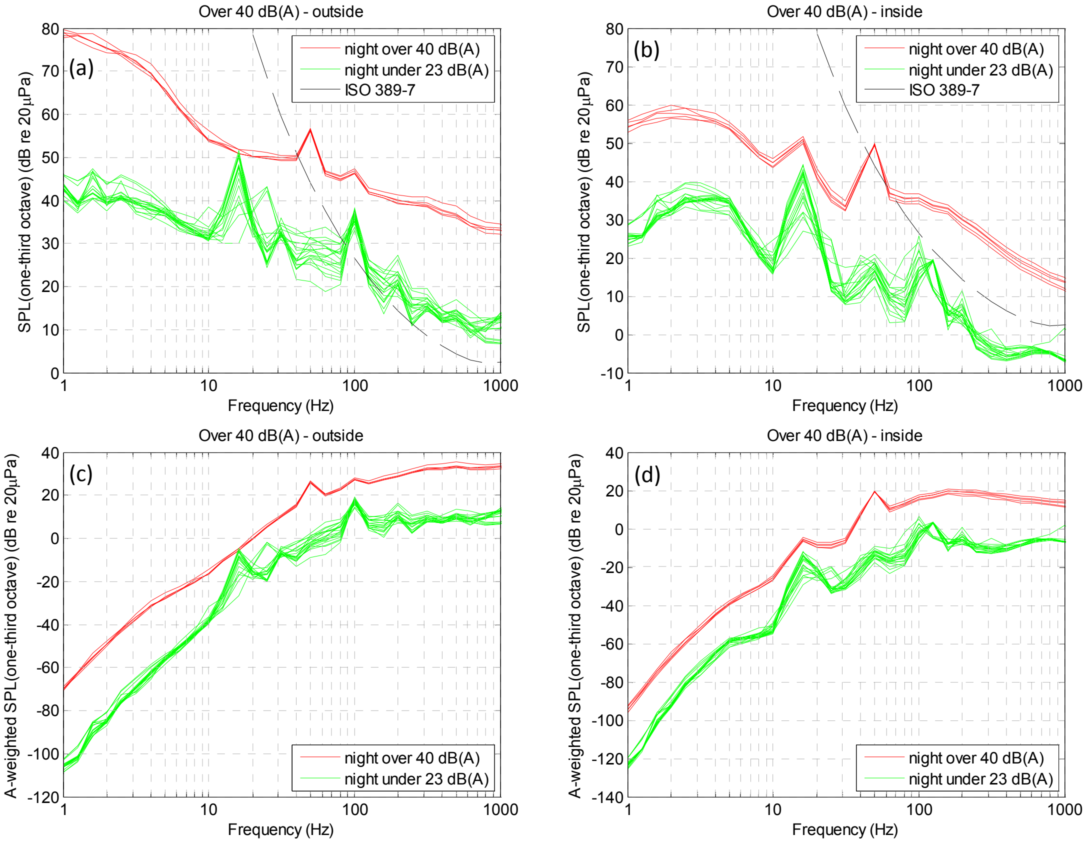


Figure 56 – Measurements exceeding 40 dB(A), Township site.

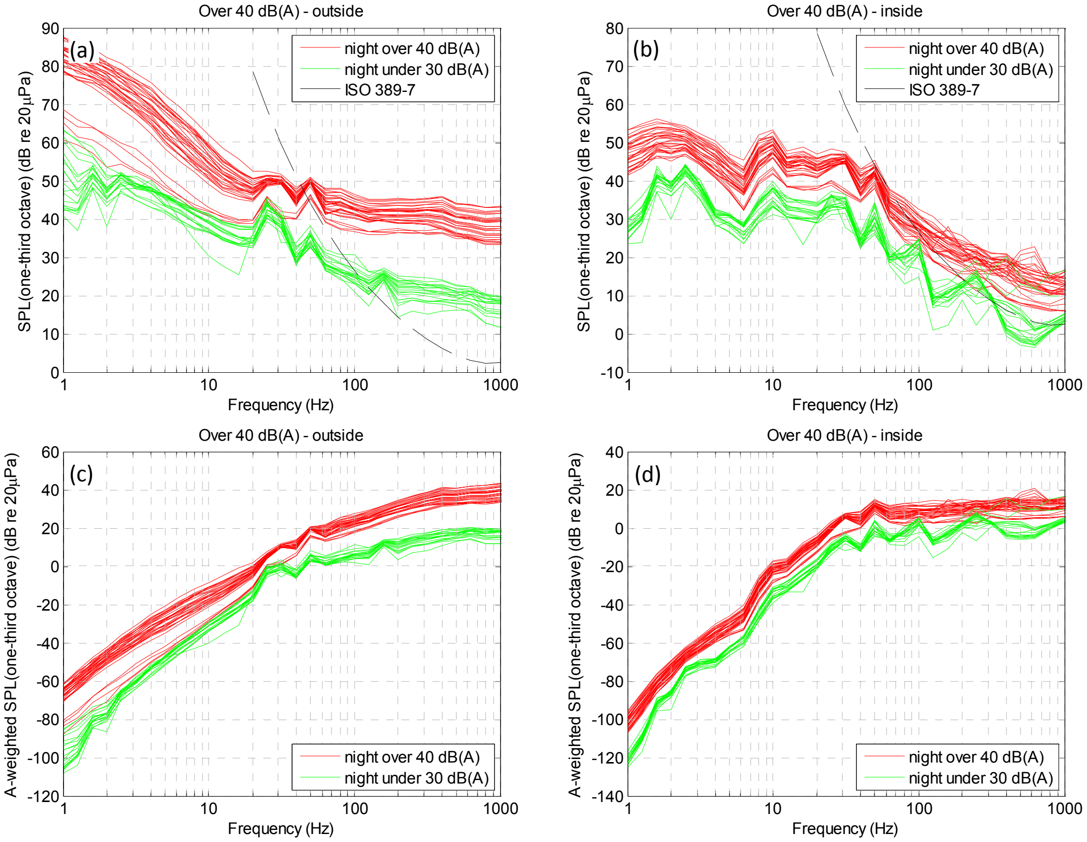


Figure 57 – Measurements exceeding 40 dB(A), North site.

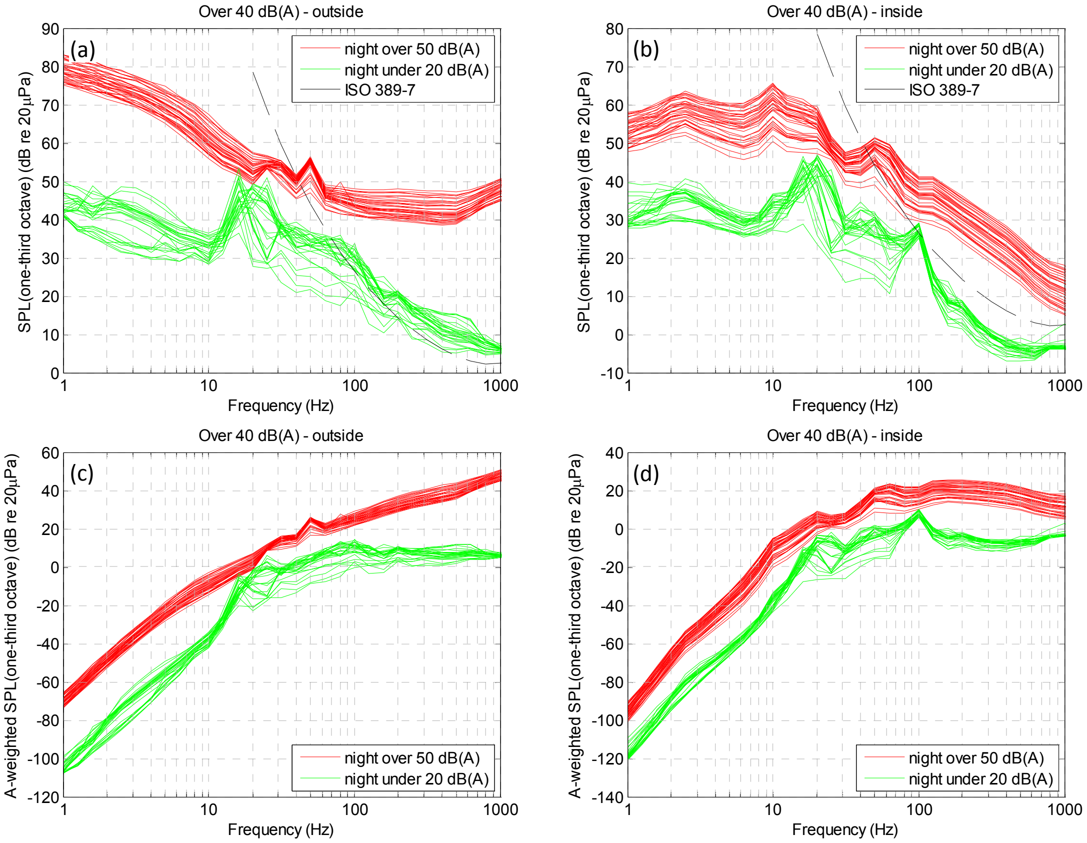


Figure 58 – Measurements exceeding 40 dB(A), West site.

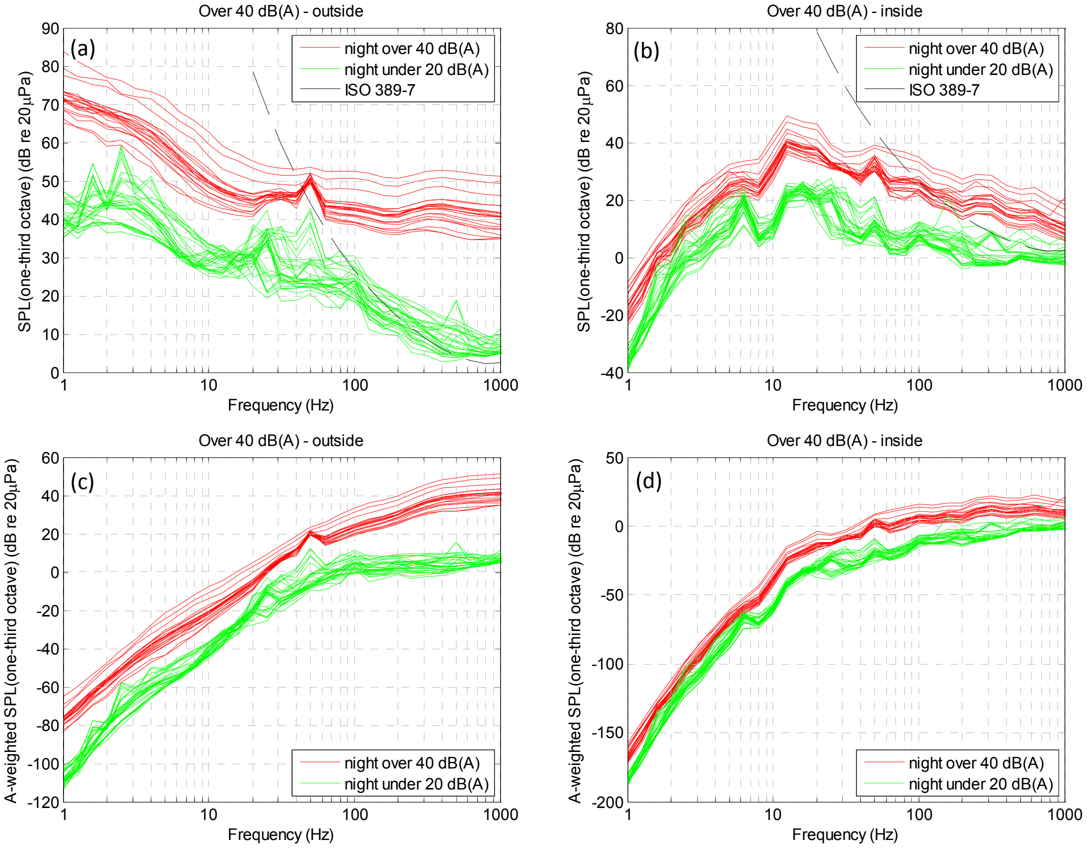


Figure 59 – Measurements exceeding 40 dB(A), East site.

8 Conclusions

Based on the findings in this report, the following conclusions can be drawn:

- For the 50 Hz third-octave band, the sound pressure level difference between shutdown and operational conditions can be higher than 25 dB for both outdoor and indoor measurements.
- The noise level in the 50 Hz third-octave band is often above the audibility threshold (ISO 389-7, 2005) when the wind farm is operating.
- The peak in the 50 Hz third-octave band would be classified as a tone according to some standards (NZS 6808:2010, 2010; ANSI S12.9 - Part 4, 2005).
  - The allowable limits should be reduced by 5 dB(A) to account for such tonal noise.
- The outdoor and indoor noise levels measured during the shutdown cases were consistently lower than those measured when the wind farm was operating.
- The most significant differences between shutdown and operational conditions can be observed when the residence is downwind from the nearest wind turbine and the hub height wind speed is greater than 8 m/s.
- The shutdown periods should have occurred during 12 am – 5 am when the contribution from extraneous sources would be minimised and the contribution from the wind farm more able to be quantified.
- For all shutdowns reported here, the closest wind turbine to the residence did not reach its rated speed of 15 m/s. In most cases, the wind speed at hub height was significantly lower than rated speed for the shutdown and adjacent times.
- The peak in the 50 Hz third-octave band is a consistent feature of the noise diary results and is often above the audibility threshold (ISO 389-7, 2005).
- A narrow-band analysis with frequency resolution of 0.1 Hz reveals distinct peaks at the blade-pass frequency and harmonics for many of the results corresponding to noise diary entries.
- The narrow-band analysis also shows the existence of tones, which occur at 23 Hz, 28 Hz, 46 Hz, 56 Hz and 69 Hz.
  - These tones have several sidebands which are spaced at the blade-pass frequency and allude to the occurrence of amplitude modulation.
- There is a good correlation between low frequency noise events and complaints registered in noise diaries.
- At many of the residences, there were many occasions during the hours of 12 am and 5 am where the outdoor noise level exceeded the SA EPA (EPA, 2009) criteria of 40 dB(A).
- The indoor limit for wind turbine hosts of 30 dB(A) recommended by the SA EPA (EPA, 2009) was exceeded on many occasions between 12 am and 5 am. This is also the no observed health effect limit for *outdoor* noise according to the WHO (2009).
- The range in the overall A-weighted levels was noticeably large indoors and could be as low as 5 dB(A) and as high as 38 dB(A). The lower value highlights that the night-time noise levels in this rural environment are sometimes so low that even low levels of wind turbine noise would be noticeable. It is plausible that the upper value is related to the presence of wind turbine noise.

- It has been shown that there can be a large variation in the results obtained by considering the L_{Aeq} as opposed to the L_{A90}, between the hours of 12 am and 5 am.
    - Since the number of extraneous noise sources is expected to be low during these night-time hours and wind turbine noise can be highly variable with time, it does not seem justified to only consider noise levels which were exceeded 90 % of the time.
- The C-weighted level was often higher for downwind conditions and hub height wind speeds greater than 8 m/s. However, consideration of the overall level with respect to recommended limits did not prove useful in identifying any low frequency noise issues.
- The L_{Ceq} - L_{Aeq} criteria was often exceeded and there was a large scatter in the data.
- The overall G-weighted level of 85 dB(G) was never exceeded however this does not preclude the possibility that infrasound was not detectable.
- The Danish low frequency noise guidelines were exceeded on a number of occasions. In general, the exceedences occurred for downwind conditions and hub height wind speeds greater than 8 m/s.
- The DEFRA criteria were exceeded on multiple occasions, usually corresponding to downwind conditions and hub height wind speeds greater than 8 m/s.

Therefore, the results show that there is a low frequency noise problem associated with the Waterloo wind farm. Therefore, it is extremely important that further investigation is carried out at this wind farm in order to determine the source of the low frequency noise and to develop mitigation technologies. In addition, further research is necessary to establish the long-term effects of low frequency noise and infrasound on the residents at Waterloo. This research should include health monitoring and sleep studies with simultaneous noise and vibration measurements.

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