5th International Conference
on
Wind Turbine Noise
Denver 28 – 30 August 2013

Sound propagation from wind turbines under various weather conditions

Olof Öhlund Uppsala University, Earth Sciences, Villavägen 16, SE-752 36 Uppsala, Sweden.
E-mail: olof.ohlund@geo.uu.se

Conny Larsson Uppsala University, Earth Sciences, Villavägen 16, SE 752 36 Uppsala, Sweden conny.larsson@met.uu.se

Summary

Continuous measurements of wind turbine sound were performed during approximately two years at two different sites in Sweden. Meteorological parameters were measured in parallel with the acoustical measurements to see the weather influence on the sound propagation. A combined effect of refraction (bending of sound ways) and ground properties was found. This meteorological effect starts to be important somewhere between 400 – 1000 m from a wind turbine and could give a meteorological variability of the expected sound level with 7 dBA during the summer and 14 dBA during snow cover conditions. A comparison between the wind turbine sound immission measurements, ISO 9613-2 and the recommended wind turbine sound propagation model in Sweden reveals that the models underestimate the highest sound levels. Sound propagation models in general need to consider the meteorological effect for better predictions at longer propagation distances.

During the half measurement period (one year) the sound level were stored 8 times per second to capture the amplitude modulation of the sound, which according to some, increases the annoyance. It was found that amplitude modulation roughly occurs 18 % of the time at a distance of 1 – 2 km from 12 wind turbines and is more common under specific meteorological conditions such as positive sound speed gradients and positive temperature gradients.

1.0 Introduction

In the light of global warming, many countries need to decrease their carbon emissons. In Sweden for example the number of wind turbines (WTs) has increased rapidly during the last years. An ambious goal of 30 TWh wind power energy year 2020 has been introduced. Wind power could have a negative effect of the local environment around the turbines through noise and visual impact (Pedersen and Waye 2004; Pedersen and Waye 2007; Pedersen and Larsman 2008; Pedersen, v d Berg, Bakker and Bouma 2009). It has also been shown that wind turbine (WT) sound is perceived more annoying than other sound sources at the same sound level (Hanssen et al 2011). One reason for this could be that WT sound is amplitude modulated in time as the blades pass through the air, often referred to as a rhythmic “swish”. This paper investigates the occurrence of amplitude modulation (AM) under various weather conditions.

Countries have different recommendations regarding WT sound. Regarding environmental planning, sound propagation models are commonly used. Accurate model predictions are important to ensure future public support of wind power. It is well known that meteorological

parameters effect sound propagation for sound sources close to the ground (Larsson 1984; Larsson and Israelsson 1991). Changes in wind and temperature with height force the sound waves to bend either upwards from the ground or downwards toward the ground, resulting in lower respectively higher sound levels. Other meteorological effects are turbulent scattering and atmospheric absorption. This paper report on the meteorological effect on elevated sound sources like WTs and the importance of including these effects in sound propagation models. We have earlier reported a meteorological variation of 6 – 14 dBA for a 10 months period at a distance of 1 – 2 km from 12 WTs (Larsson and Ohlund 2012).

Long-time measurements of WT sound have been made continuously during approximately two years at two different WT sites. The measurement periods (Dragaliden: December 2010 – December 2012, Ryningsnäs: August 2010 – June 2012) cover the seasonal variations in the weather. Acoustical, meteorological and operational data were collected in parallel throughout the entire period. The measurements were a part of a larger project (Larsson and Ohlund 2011) which aims for a better understanding of WT sound propagation in the atmospheric boundary layer.

2.0 Measurements

2.1 Meteorological measurements

Meteorological information is collected from a number of towers. The setup is similar at both sites. An 18 m high weather mast placed in connection with the microphone cover the meteorological parameters inside the forest. This mast in mounted with WindSonic anemometers and ventilated temperature sensors at four heights above the ground. Air pressure and relative humidity is also measured at 1.5 m height. In addition to the short mast, information up to 120- 150 m height is gathered from weather masts in the vicinities. At the Dragaliden site one 150 m high meteorological tower is located 10 km to the southeast and one 123 m high mast 7 km west of the acoustical station. The tower southeast is located on a hill similar in shape and height as the Dragaliden and the meteorological conditions are expected to be the same. The tower west of the station is located on a 50 m higher hill and is only used in a period in the summer when the southeast tower did not function after an attack from a bear. In overall this gives good knowledge of how meteorological parameters vary vertically. The turbulence intensity (TI) in this paper is defined as:

$$TI = u'/U \qquad (1)$$

where u' is the standard deviation and U the mean of the wind speed, both calculated for periods of 10 minutes. The time resolution of the wind speed was 1 s.
The effective sound speed (c_{eff}) in a specific direction is defined as:

$$c_{eff}(z) = 20.05\sqrt{(1 + 0.61q)T} + u(z) \qquad (2)$$

where the first term on the right-hand side of the equation is the sound speed in the atmospheric boundary layer without the influence of the wind, q is the specific humidity (kgkg^{-1}), T is the temperature (K) and $u(z)$ is the wind speed (ms^{-1}) at height z (m) in a specific direction. In this paper all sound speeds refers to the effective sound speed calculated with eq. 2.

2.2 Acoustical measurements

The sound level meter is placed at 1.5 m height inside the forest. It has not been possible to follow the standard procedure with measurements on a ground plate when doing these measurements because snow depth could reach above 1 m at the sites. Grids of long cables through the forest power the stations. A Nor140 sound level meter equipped with a Nor1214 outdoor ½'' microphone was used. It is a class I instrument and measures 1/3 octave bands in the range 6.3 Hz – 20 kHz. Data were stored once a second except for a 1 year period of AM studies, when data was stored every 125 ms. L_{Aeq} and the percentiles L_1, L_5 and L_{95} for every 10-minute average were calculated. Calibrations are carried out when visiting the sites.

2.3 Sites

2.3.1 The Dragaliden site

The Dragaliden site is located in northern Sweden (65.44°N, 20.52°E). Twelve Enercon E-82 (2,0 MW) WTs with hub heights of either 108 or 138 m stand on the hill of Dragaliden, see fig. 1. The acoustical measurements take place inside the forest around 1 km northeast of the closest turbine. The little village of Strömnäs with few inhabitants is located around 1 km north of the measurement station and the ambient sound level is often low.

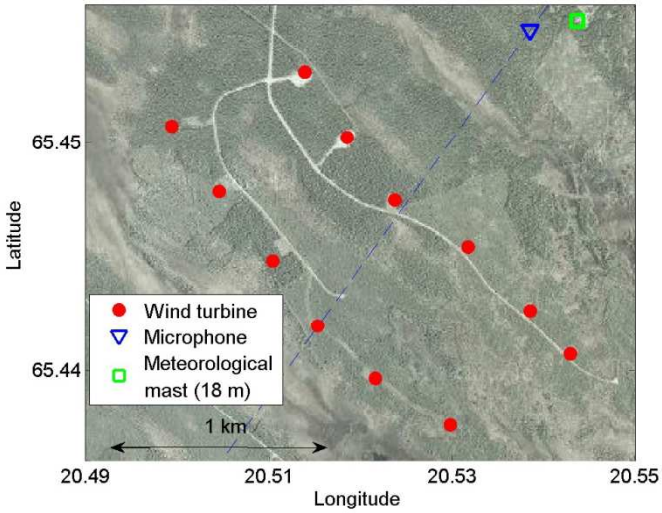

Figure 1. Map of the Dragaliden site. Throughout this paper, sound speed gradients for the Dragaliden site are calculated as the vertical difference in sound speed along the dashed line, with a positive direction toward the northeast (courtesy of Google Earth).

2.3.2 The Ryningsnäs site

The Ryningsnäs site is located in southern Sweden (57.28°, 15.99°E). Two Nordex 2500 LS (2.5 MW) turbines with hub height of 80 and 100 m stand in the flat forested area, see fig. 2. The acoustical measurement station is placed in the forest around 400 m east of the tallest turbine. The surroundings are quiet. A road located 1.7 km in the south carry some traffic but are not expected to influence the measurements.

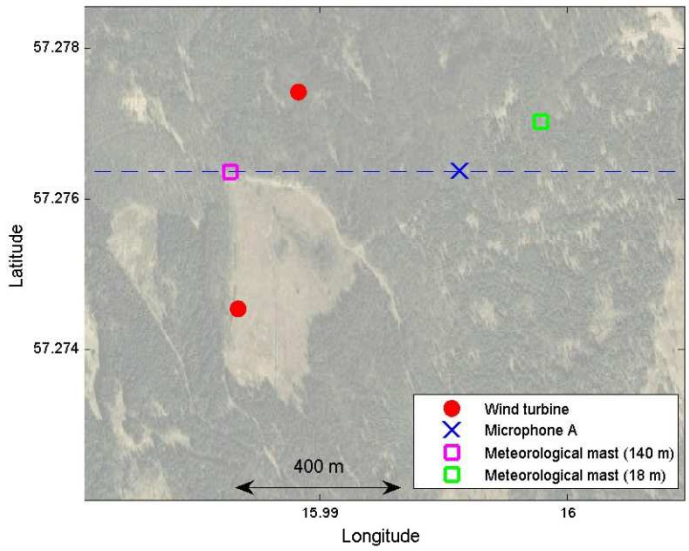

Figure 2. Map of the Ryningsnäs site. Throughout this paper, sound speed gradients for the Ryningsnäs site are calculated as the vertical difference in sound speed along the dashed line, with a positive direction toward the east (courtesy of Google Earth).

3.0 Method

3.1 Selection of data

WT sound immission measurements are difficult to accomplish. At larger distances the measurements are more difficult because of the low WT sound levels measured. The main disturbances at our measurements sites is wind induced sound from the vegetation and birds singing (spring time). Careful documentation of the sound environment around the sites has been made and a number of measurement criteria (for the 10 minutes measurements) have been set to avoid disturbances of the WT sound measurements:

- L_5 - $L_{95} \leq 4$ dBA
- $L_1 - L_{95} \leq 15$ dBA
- The A-weighted 1/3 octave band sound from 800Hz and above should not contribute to more than 1.5 dB to the total A-weighted sound level if the sound is above 23 dBA.
- The emitted sound power from the turbines should by calculation (free field propagation from a point source) contribute to at least 30 dBA at the imission point.

The first two criteria are based on the fact that sound disturbances change the sound level suddenly while the WT sound level is quite steady over time. The third criterion excludes measurements with wind induced sound from the vegetation and is based on results from a model (Bolin 2009). The WTs also need to operate at a certain power to be included in the long term analysis (criterion four). The selected measurements presented in this paper are taken from a period of approximately two years (Dragaliden: December 2010 – December 2012, Ryningsnäs: August 2010 – June 2012) and represents 11 and 13 % of the total measurement respectively.

3.2 Normalizing sound immission data

In this paper the deviation in the sound level from an expected value is presented during different weather situations. The expected value is calculated as follows.
Emitted sound from the wind turbines were calculated using operational data and manufacturer´s specifications. Continuous functions of the electrical output and sound power spectra in 1/3 octave band from 50 Hz to 10 kHz were obtained by fitting second order polynomials between a number of discrete (electrical power- sound power spectrum) relations.

Validation of the manufacturer´s specifications was not possible during this study. Some uncertainty in the sound power level could therefore be expected.
The relative sound pressure level (ΔL) was obtained by relating the measured sound pressure level to the calculated value:

$$\Delta L = L_{pA} - 10\log \sum_i 10^{\left(L_{WA_i} + D_{Ii} - 10\log\left(4\pi R_i^2\right) - \alpha R_i\right)/10} \quad (3)$$

where L_{pA} is the measured sound pressure level at the immission point, L_{WA} is the calculated emitted sound power level from the i:th turbine, D_{Ii} is a directivity correction (Friman 2011) depending on the angle between the i:th turbine rotor plane and the immission point, R_i is the distance in meters between the i:th source and the immission point and α is the atmospheric absorption coefficient per meter in the current atmosphere.

3.3 Quantifying amplitude modulation

Sound from WT could be amplitude modulated at a certain receiver position which is often referred to as periodic “swish” sound. This phenomenon has been reported by many (van den Berg 2004, Di Napoli 2011) and various explanations has been proposed (Oerlemans et al 2007, van den Berg 2004). In this paper a method using a fast Fourier transform (Lundmark 2011) has been used to quantify AM in the presence of other typical background sounds. The method analyses a numeric time series of A - weighted sound pressure levels adjusted to zero mean value (calculated from the 10 - 630 Hz 1/3 octave bands only) for a time window of 15 s. The frequency limit was chosen because WT sound often contains a clear low frequency component at large distances (due to atmospheric absorption). The measurements should be performed with at least 8 Hz sampling frequency, using fast (F) time weighting to detect the periodic sound. No window function is used in the FFT; instead, it is a frequency analysis that gives a linear root mean square (RMS) scaled spectrum. The FFT will generate an amplitude modulation spectrum for every 15 s period (seen in fig 3, to the right), which can quantify AM frequency and strength. Based on observations at the sites and studies of different amplitude modulation spectra, a definition of when a measurement is AM was set:

- The peak RMS-value between 0.6 – 1.0 Hz is ≥ 0.4 during a 15 s long period

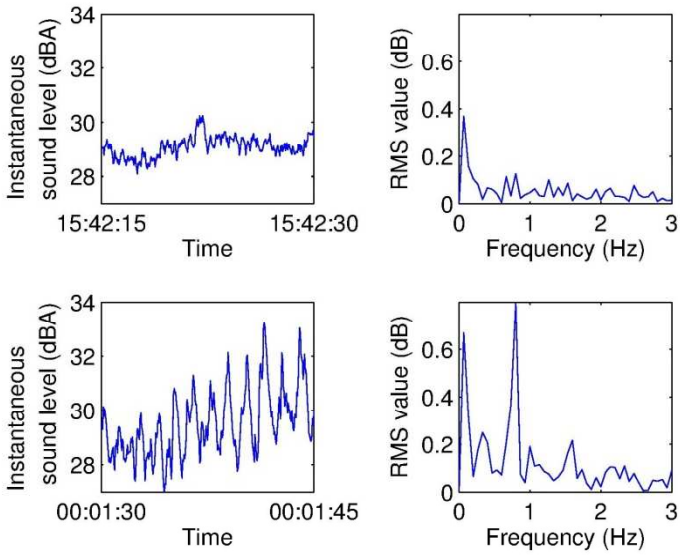

Figure 3. Sound measurements from the Dragaliden site the 20 July 2011. Instantaneous sound level and corresponding RMS-value (AM if ≥ 0.4) is shown for two 15 s long periods during day (no AM) and night (AM).

4.0 Results

The WT sound and meteorological parameters were measured in parallel for approximately two years at the different sites. In fig. 4 and 5 the relative sound pressure level is shown for different sound speed gradients. The sound speed gradient refers to the vertical difference in sound speed along a line from the centre of the wind turbines to the immission point and is calculated with eq. 2 at two different heights. Data is divided into conditions with and without snow cover. The bars give one standard deviation of the data in each bin. Numbers indicate how many selected 10 minute measurements there are in each bin. As seen in fig. 4 no clear meteorological effect can be seen at a propagation distance of around 400 m. All mean ΔL values are positive (from +2 to +5 dBA) maybe due to the presence of the ground. For sound speed gradients close to zero the relative sound pressure levels are somewhat lower. In fig. 5 the relative sound pressure levels for different sound speed gradients are shown for the Dragaliden site. The propagation distance is 1 - 2 km at this site. In general high ΔL (+3 to +6 dBA) are found for positive sound speed gradients and low ΔL (-9 to -2 dBA) for negative sound speed gradients. The mean value of ΔL varies between 7 - 14 dBA depending on ground conditions and refraction. In fig. 5, a large difference between snow and no snow conditions can be seen. Ground attenuation seems to be more effective during strong negative and positive sound speed gradients when snow is present. For moderate downward refraction the ground type is less important according to fig. 5.

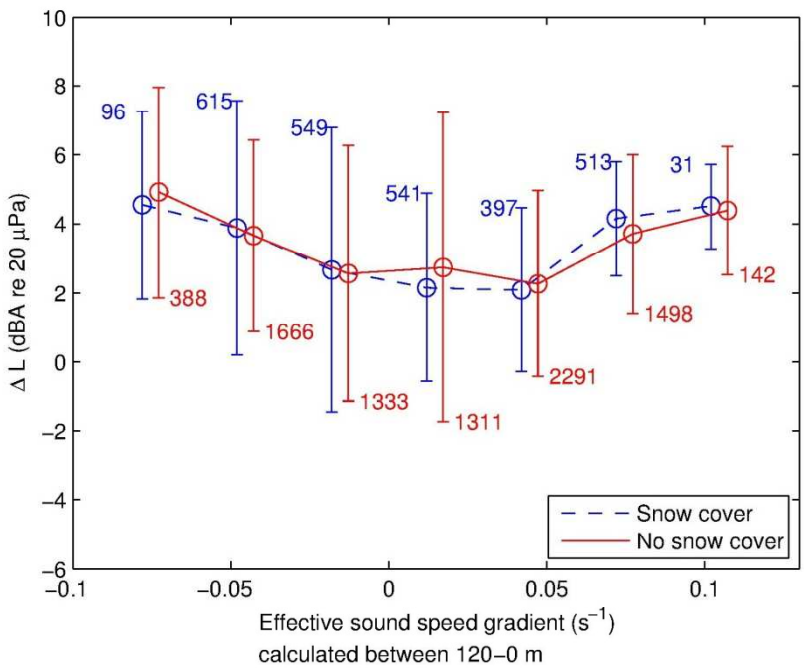

Figure 4. Relative sound pressure level (calculated with eq. 3) for different effective sound speed gradients and ground properties for the Ryningsnäs site. The effective sound speed gradient is calculated from 120 m height to the ground. The numbers indicate the total number of selected measurements within each bin. The bars indicate one standard deviation of the selected data.

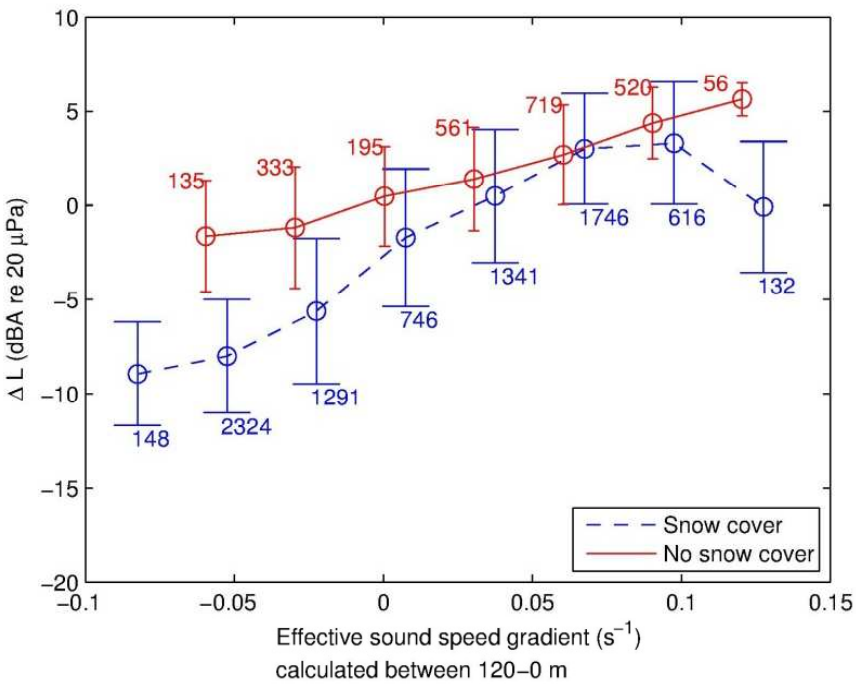

Figure 5. Relative sound pressure level (calculated with eq. 3) for different effective sound speed gradients and ground properties for the Dragaliden site. The effective sound speed gradient is calculated from 120 m height to the ground. The numbers indicate the total number of selected measurements within each bin. The bars indicate one standard deviation of the selected data.

Continuous measurements of the instantaneous sound pressure level were recorded 8 times s^{-1} from 19 August 2011 to 19 August 2012 at the two measurement sites. All data were the free field value assuming spherical divergence of the sound energy exceeded 30 dBA was used in the analysis of AM. Fig. 6 shows how often AM occurred under various conditions for the Ryningnäs site. AM percent is defined as AM time divided by total time in a specific sector. AM at a propagation distance of 400 m is more common at certain immission sound levels as seen in fig. 6a. The sound seem to be more amplitude modulated for increasing sound levels up to around 40 dBA and then less amplitude modulated. This is probably an effect of increased masking for the highest sound levels. In fig. 6 d) the amount of AM is plotted against the sound speed gradient. It is seen that this parameter is important for the occurrence of AM. More AM during moderate downward and upward bending of the sound waves. The temperature gradient close to the surface (seen in fig. 6 e) shows that AM is more common under positive gradients which often occurs at evenings, nights and mornings. In fig. 6 f) the connection between the wind speed gradient between 120 and 80 m and the amount of AM is shown. More AM is found for large wind shears close to the WTs. Note that the wind shear is calculated independent of the wind direction.

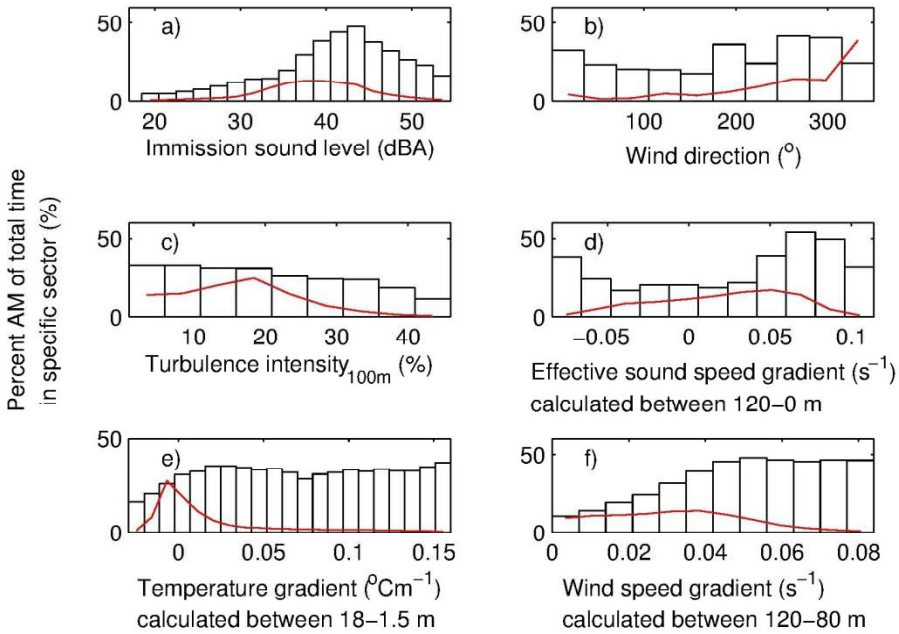

Figure 6. Percent of AM (AM measurement time divided by total time) in a specific sector for the Ryningsnäs site during a one year period. The red line indicates the amount of measurements in each sector (percentage of total measurements in each sector).

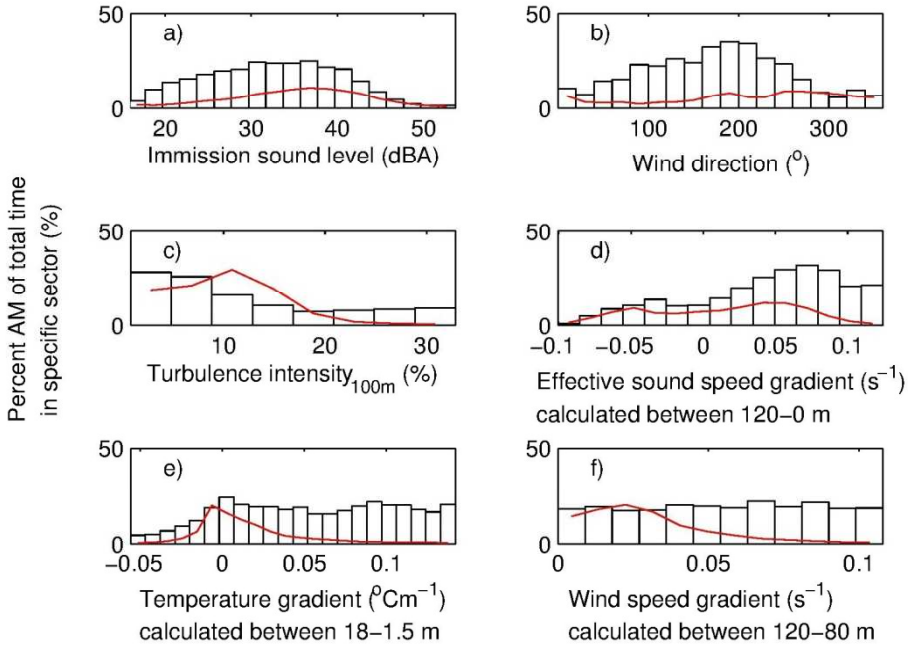

Figure 7. Percent of AM (AM measurement time divided by total time) in a specific sector for the Dragaliden site for a one year period. The red line indicates the amount of measurements in each sector (percentage of total measurements in each sector).

Fig. 7 shows the long-term results for the Dragaliden site. The propagation distance is now approximately three times larger and the terrain is varying. Similar patterns as for the Ryningsnäs site can be seen with some differences. At the Dragaliden site AM seems to very rare under upwind conditions seem both in fig. 7 b) and 7 d). Probably this is due to upward bending of sound waves resulting in less WT sound reaching the receiver. In specific wind directions AM can be detected 30 - 40 % of the time at this site. The high turbulence intensities seen in fig. 7 c, seem to decrease the occurrence of AM. For the temperature gradient seen in

fig. 7 e), the amount of AM is larger for positive temperature gradients. Less AM is found for large wind shears in fig. 7 f) in contrast to the shorter distance in fig. 6 f). The amount of time we detect AM at the Ryningsnäs and Dragaliden site is 30 and 18 % respectively, of the total time operating.

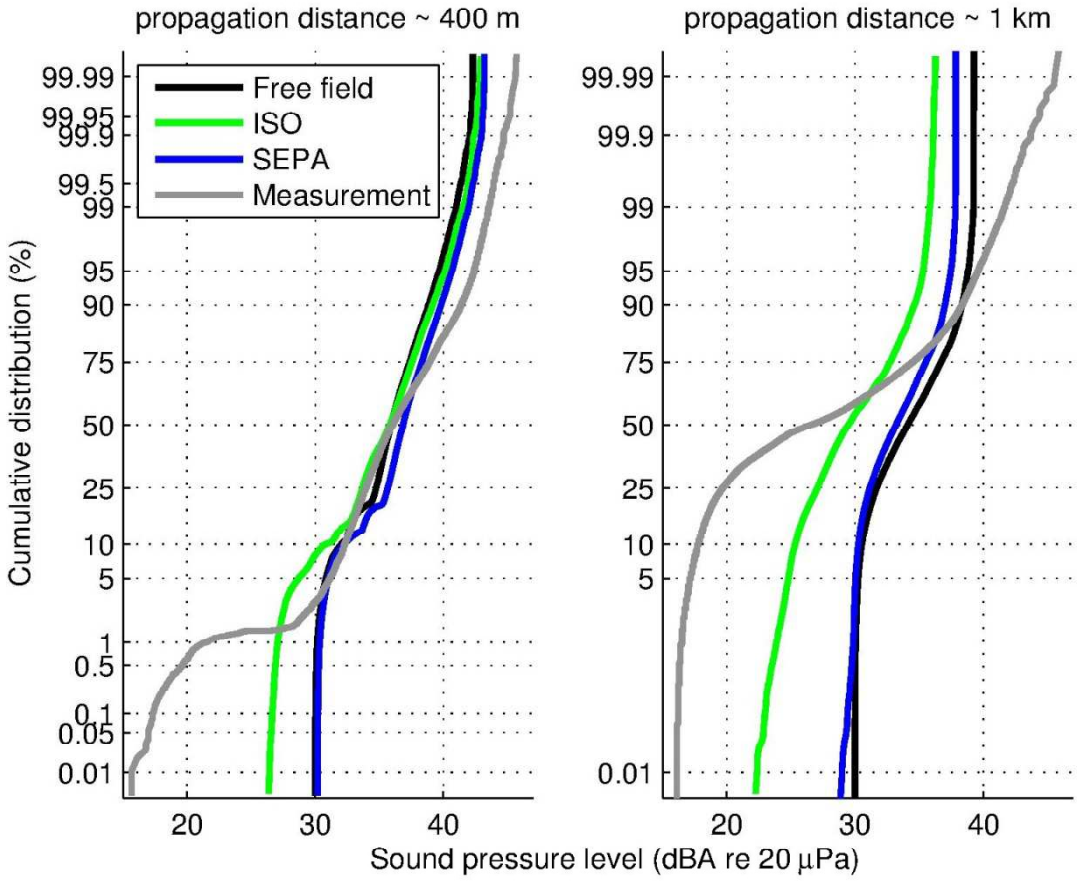

Figure 8. Cumulative distribution of measured WT sound levels and calculations with different models. ISO refers to (ISO 9613-2), SEPA is the turbine noise model recommended in Sweden (Swedish Environmental Protection Agency 2010), Free field is spherical divergence of the sound energy without any ground present.

Fig. 8 shows cumulative distributions of measured WT sound levels, predictions by the ISO standard and free field spherical spreading from a point source at the two sites. As seen in fig. 8 the free field values never go below 30 which is expect because it is a criterion that the measurements must pass (see sec. 3.1). The SEPA model is the WT noise model recommended in Sweden (Swedish Environmental Protection Agency 2010). The SEPA model assumes spherical divergence of the sound energy on a half sphere and up to propagation distances of 1000 m the total sound emitted should be reduced with a fixed value of the atmospheric absorption. For longer propagation distances the sound emission spectrum of the turbine need to be considered and atmospheric and fixed absorption coeffients for different octave bands (which give high attenuation) should be used. The calculations with the ISO standard for outdoor sound propagation (ISO 9613-2) have been done using the data collected for each measurement period passing the criteria. Directivity effects have been calculated from nacelle wind direction and investigations by Friman (Friman 2011). Atmospheric absorption has been calculated using the standard (ISO 9613-1) and meteorological parameters close to the ground. Sound power is obtained by the method decribed in section 3.2. Porous ground was used in all ISO calculations. Both the SEPA model and ISO standard are designed to calculate the sound pressure level downwind of a sound source. Fig. 8 refers to measurements in all wind directions, so a deviation for the low sound levels could be expected. However as far as people living nearby WT are concerned, it is the highest sound levels that are most relevant

and need to be predicted correctly. It is seen in fig. 8, that neither the SEPA model nor the ISO standard captures the variations in the WT sound levels in general. Fig. 8 shows that for the shorter propagation distance more than 25 % of the WT immission measurements exceed the ISO 9613-2 predictions. For the longer propagation distance the percentage exceeding the measurements are similar, but underestimation of the model is larger in sound level.

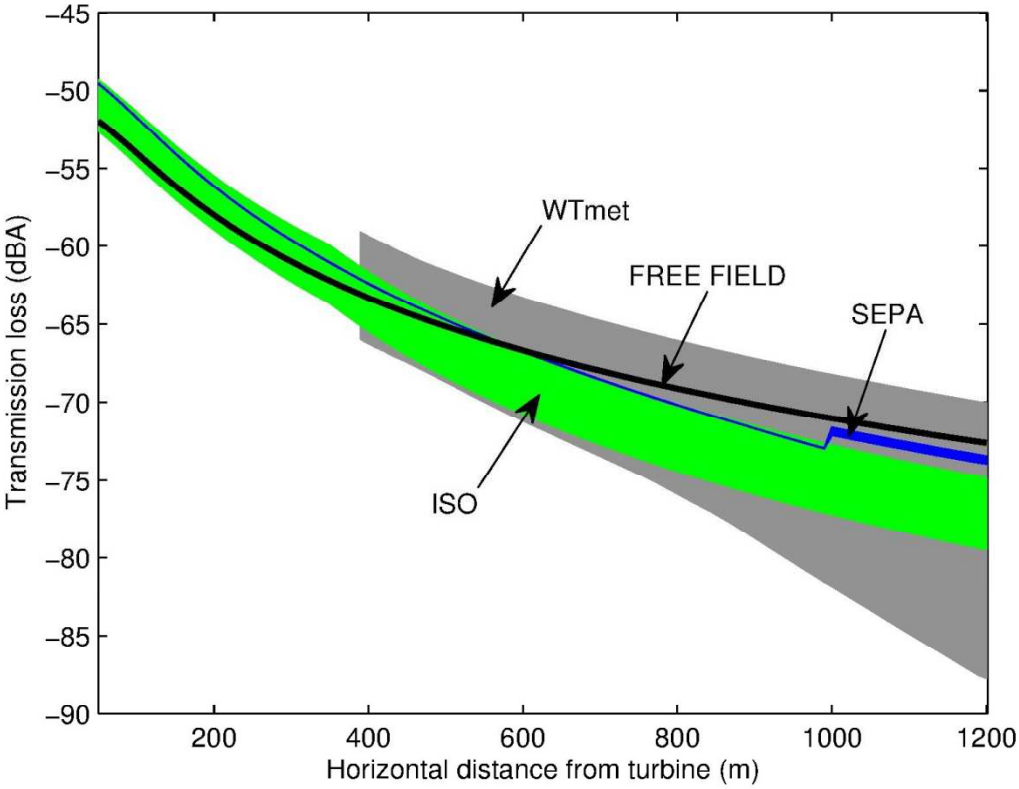

Figure 9. Calculated transmission loss from a WT during one year, using different models and meteorological data from southern Sweden. ISO refers to (ISO 9613-2), SEPA is the turbine noise model recommended in Sweden (Swedish Environmental Protection Agency 2010), FREE FIELD is spherical divergence of the sound energy without any ground present and WTmet is a simple empirical model based on the measurements presented in this paper (see below).

The empirical model WTmet (which is based on the measurements presented in this paper) works as follows:

$$L_{pA} = L_{WA} - A_{div} + D_I - A_{atm} + A_{met} \qquad (4)$$

where L_{pA} is the immission sound level, L_{WA} is the emission sound spectrum, A_{div} is spherical divergence of the sound energy from a point source, D_I is a directivity correction from (Friman 2011), A_{atm} is attenuation due to atmospheric absorption calculated with (ISO 9613-1) and A_{met} is a meteorological correction (from eq. 3) depending on distance from the turbine and sound speed gradient along the propagation path. ΔL from fig. 4 at 400 m is interpolated linearly to the ΔL values of fig. 5 assuming propagation distance of 1200 m for every sound speed gradient. This gives a meteorological correction A_{met} for every distance from 400 m to 1200 m depending on the sound speed gradient.

It is seen in fig. 9 that the meteorological effect grows with distance. ISO 9613-2 used for porous ground also introduce larger variations at larger distances due to atmospheric absorption. The directivity correction also introduces a variation (which is independent of distance) due to shifting wind direction during the year. It should be pointed out again that both

ISO 9613-2 and the SEPA model are designed to calculate the sound pressure level downwind of a sound source. Fig. 9 refers to measurements in all wind directions, so perfect agreement could never be reached. It is however clear from fig. 8 and 9 that the models used for WT sound propagation do not capture the optimal sound propagation conditions that sometimes occur in the atmospheric boundary layer thus resulting in prediction of to low WT sound levels. For longer propagation distances than 600 m, as seen in fig. 9, free field propagation gives a better estimate than both ISO 9613-2 and the SEPA model for the worst case scenarios. The prediction errors for the ISO standard seem grow with distance while the SEPA model have a more constant error as the propagation distance grow. As seen in fig. 9 for a propagation distance of slightly more than 1 km the ISO standard could underestimate the WT sound level with 5 dBA and the SEPA model could underestimate the levels with 3 dBA.

5.0 Discussion and conclusion

WT sound immission measurements are difficult to perform. The difficulties grow with distance from the WT as the WT levels get closer to the background level. The measurements presented in this paper have been performed inside forests. The winds are lower inside a forest canopy compared to an open field position. The forest measurement position will reduce the wind noise in the microphone and could also be a better measurement position than in an open field close to some single trees where the wind induced sound from the vegetation will be high. Doing unmanned long-term measurements, which is necessary to capture the variations in the weather, calls for good measurement criteria.

Sound propagation from wind turbines are strongly affected by meteorological conditions. The effects start to be important somewhere between 400 - 1000 m from turbines and increase with distance. For 12 WT at 1 - 2 km distance a variation of 7 - 14 dBA was found due to a combination of ground properties and refraction. The result shows that ground conditions and refraction are closely linked. Lower sound levels than expected are found for negative sound speed gradients and higher sound levels for positive sound speed gradients, both during the winter and summer. The attenuation during negative sound speed gradients is much larger during snow cover condition. For strong positive sound speed gradients snow cover conditions also seem to attenuate the sound more than for bare ground. This is probably an effect of multiple reflections of sound rays during strong downward bending of the rays. For moderate downward refraction of WT sound however, there is no clear difference to two ground types.

Amplitude modulation of WT sound is found more frequently under certain meteorological conditions. The phenomenon is roughly observed 30 % of the time at a distance of 400 m and 18% of the time at a distance of 1 km. The reasons why WT sound sometime is amplitude modulate is not fully understood. This paper shows that AM is more common during positive sound speed gradients, positive temperature gradients and for higher immission sound levels. This means that both the WT sound level and the amount of AM will often increase during evening, night and morning. AM is probably depending on both conditions in the propagation path (which can strengthen interference of several turbines at an immission point) and properties of the sound source.

A comparison between the measured WT sound immission levels and calculations with ISO 9613-2 shows that the model needs to include meteorological effects better. The highest sound levels (which are the most disturbing) are predicted to low. The ISO 9613-2 underestimates the WT sound levels with approximately 5 dBA at distance of slightly more than 1 km. Including a meteorological correction factor (in addition to the long-term correction which is already there) would make the model more precise and also valid in upwind conditions.

ACKNOWLEDGEMENTS

This study was financially supported from the Swedish Energy Agency. We also thank Svevind, Vattenfall, Visby Energi, Nordex and Enercon for charring operational- and meteorological data. Gunnar Lundmark, of Lundmark Akustik & Vibration and Professor Emeritus Kjell Ahlin at Blekinge Institute of Technology helped with the method for AM detection.

References

Bolin B. (2009), Prediction method for wind-induced vegetation noise, Acta Acust. United Ac. 95, 607-619

Di Napoli, C. (2011), Long distance amplitude modulation of wind turbine noise. Proceedings from Wind turbine noise, Rome, Italy

Friman, M. (2011), Directivity of sound from wind turbines, Thesis for the degree of Master of Science, The Marcus Wallenberg Laboratory for Sound and Vibration Research

Hanssen, S.A., Vos, H., Eisses, A.R., and Pedersen, E (2011). A comparison between exposure-response relationships for wind turbine annoyance and annoyance due to other noise sources, J. Acoust. Soc. Am. 130, 3746-3753

ISO 9613-1 (1996), Attenuation of sound during propagation outdoors - Part 1: Calculation of the absorption of sound by the atmosphere, International Standards Organization

ISO 9613-2 (1996) Attenuation of sound during propagation outdoors - Part 2: General method of calculation, International Standards Organization

Larsson, C. (1984), Effects of meteorological parameters on sound propagation, Abstracts of Uppsala Dissertations from the Faculty of Science, 714

Larsson, C. and Israelsson S. (1991) Effects of meteorological conditions and source height on sound propagation near the ground, Appl. Acoust. 33, 109

Larsson, C., Ohlund, O. (2011) Measurements of sound from wind turbines, in Fourth International Meeting of Wind Turbine Noise, INCE/Europe, Rome, Italy

Larsson, C., Ohlund, O. (2012) Variations of sound from wind turbines during different weather conditions, Proc. Inter-Noise 2012

Lundmark, G. (2011) Measurement of swish noise, a new method, in Fourth International Meeting of Wind Turbine Noise, INCE/Europe, Rome, Italy

Oerlemans S., Sijtsma P., and Lopez B. M. (2007) Location and quantification of noise sources on a wind turbine, J. Sound Vib. 299, 869-883

Pedersen, E. and Waye, K.P. (2004) Perception and annoyance due to wind turbine noise – a dose- response relationship, J. Acoust. Soc. Am. 116(6), 3460-3470

Pedersen, E. and Waye, K.P. (2007) Wind turbine noise, annoyance and self-reported health and well-being in different living environments, Occupational and Environmental Medicine, 64(7), 480-486

Pedersen, E. and Larsman, P. (2008) The impact of visual factors on noise annoyance among people living in the vicinity of wind turbines, Journal of Environmental Psychology, 28(4), 379-389

Pedersen, E., v d Berg, F., Bakker, R., and Bouma J. (2009) Response to noise from modern wind farms in The Netherlands, J. Acoust. Soc. Am. 126(2), 634-643

Swedish Environmental Protection Agency (2010), Noise from wind turbines, Report 5933, (in Swedish)

van den Berg, G. P. (2004) Effects of the wind profile at night on wind turbine sound, J. Sound Vib. 277, 955-970