



Variations of sound from wind turbines during different weather conditions

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Long-term measurements of sound from wind turbines show variations of the order of 6 - 14 dBA at some distance from the source. The meteorological conditions change over the day and the year and vary a lot depending of the terrain conditions. The meteorological parameters govern both the wind turbine sound level and the sound propagation conditions. In an extensive measurement program, with economical support from the Swedish Energy Agency, long-time measurements of meteorological effects on sound propagation from wind turbines are performed at three sites in Sweden. The measurements are performed during 1-2 years. Sound propagation is studied in a 1) forest area, 2) over a water bay and 3) over heterogeneous terrain. The first two sites are located in the southern part of Sweden and the third is located in the northern part of Sweden. The aim of the project is to improve the knowledge about sound propagation from wind turbines and especially over varying terrain and different weather conditions. The hub height of the studied wind turbines varies from 80 - 138 m. The result shall be improved sound propagation models, updated measuring requirements, validation of modeled sound levels and methods for deriving meteorological input data for a sound propagation model. In this paper preliminary results from the first 10 months are presented.

1 INTRODUCTION

The large interest for renewable energy sources has increased the interest in wind energy. One of the issues today is to derive accurate models to be able to predict the wind turbine sound level at a certain distance. This is difficult because the sound propagation conditions change depending on the weather.

Wind turbines have earlier been placed in open fields but localization in forest areas have

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increased especially in Sweden. Earlier studies have shown large effects of meteorological conditions on the sound propagation. Differences in sound level of the order of 20 dB for a point source close to the ground has been found¹.

Changes in wind and temperature with height forces the sound waves to bend either upwards from the ground or downwards toward the ground resulting in lower respectively higher sound levels. Other effects are turbulent scattering and atmospheric absorption. The aim of this study is to look at the meteorological influence on the sound at two inland wind turbine sites in Sweden. Both meteorological and acoustic data presented in this paper has been collected between 1 December 2010 and 1 October 2011. A shorter period of eight weeks is used for studying amplitude modulation of wind turbine sound at the same sites. Results from periods up to two years will be reported later.

2 MEASUREMENTS

The two sites are both in forest areas but with different terrain conditions.

2.1 The Dragaliden site

The site, see figure 1, is located in north Sweden (65.44°N, 20.52°E) with hills stretching around 400 – 500 m above sea level. The area is covered by forest and swamp. The little village Strömnäs with very few inhabitants is situated around 1 km north of the long-term measuring station and the ambient sound level is very low. Twelve Enercon-E82 (2.3 MW) wind turbines with hub height 108 and 138 m operate at the hill of Dragaliden. It is the first wind turbines in a large planned wind turbine park.

2.2 The Ryningsnäs site

The site, see figure 2, is located in south Sweden (57.28°N, 15.99°E) in a very quiet forest area. A road located 1.7 km south of the long-term measuring station carrying some traffic. A road located 1.7 km south of the long-term measuring station carrying some traffic. Two Nordex 2500 LS (2.5 MW) with the hub heights 80 and 100 m stand in the flat forest area.

2.3 Acoustic measurements

The sound measurements are carried out 1.5 m above ground inside the forests with a Norsonic Nor140 sound level meter. A Nor1214 outdoor ½” microphone with rain hood and dust mesh are used. It is a class I instrument and measures 1/3-octave bands between 6.3 Hz – 20 kHz. L_{Aeq} and the percentiles L_1 , L_5 and L_{95} for every 10-minute average were calculated. Measurements every 125 ms were also stored for investigation of the amplitude modulation, AM, of wind turbine sound. The data are downloaded with a modem. The stations are connected to main power by long cables. Calibrations are carried out when visiting the sites.

2.4 Meteorological measurements

Weather information is measured in a number of towers in the vicinities to the stations. Both sites have similar meteorological measuring equipment. An 18 m short meteorological mast placed in the forest with WindSonic anemometers and ventilated temperature sensors at the height 0.5, 1.5,

5.0 and 18 m above ground. Wind speeds, wind directions and temperatures are measured at the same heights. The air pressure and the relative humidity are measured at 1.5 m height. Taller towers are also used at both sites.

At the Dragaliden site one 150 m high meteorological tower is located 10 km to the southeast and one 123 m high 7 km west of the measuring 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.

At the Ryningsnäs site a 140 m meteorological tower, with sensors at 7 heights between 25-140 m is placed close to the wind turbines, see figure 2.

3 RESULTS

The measured sound levels from the wind turbines are very low compared to many other human made sound sources. It is necessary to have low background sound levels when measuring wind turbine sound. Measurements of wind induced sound in vegetation, sound incidents from fly overs, human and animal activities must be rejected and only undisturbed measurements are chosen for the analyzes.

3.1 Normalizing sound imission data

Operational data from the wind turbine owners have been obtained. The emitted sound power was related to the electric output of the wind turbines by use of the manufacture specifications. The sound power level for each 1/3-octave band between 50 - 10 kHz was calculated.

The relative sound pressure level ΔL was calculated as the difference between the measured imission sound level and free field geometrical spreading of sound energy from a point source corrected for atmospheric absorption. The deviation, between the measured imission sound level and the calculated sound level are then given as a relative sound pressure level.

3.2 Selection of long-term data

Criteria for when the wind turbine sound is the dominant sound was set based on observations of the sound climate at the measuring sites. The criteria for a 10 minutes measurement are:

- $L_5 - L_{95} \leq 4$ dBA
- $L_1 - L_{95} \leq 15$ dBA
- The A-weighted 1/3 octave band sound from 800 Hz 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 a disturbing sound incident change the sound level a lot during a short time, which the wind turbines would not do. The third criterion further insures that vegetation induced sound isn't influencing the measurement. The wind turbine also needs to operate at a certain power and the lower the sound level the more sensitive to disturbances are also the measurements.

The selected measurements presented in this paper are for 10 months (1 December 2010 – 1 October 2011) represents 15.0 and 18.1 % of the total measurement time Dragaliden and Ryningsnäs respectively.

Figure 3 and 4 show the relative sound pressure level during different sound speed gradients for different ground conditions. At the distance of 1 km to the closest wind turbine at Dragaliden,

see figure 3, variations of around 6 - 14 dBA depending on the ground conditions are found. The differences show the strong coupling between refraction and ground attenuation.

Much lower sound levels are measured during upward bending (negative sound speed gradient) compared to downward bending (positive sound speed gradient).

At closer distance, Ryningsnäs (400 m from the closest wind turbine) in figure 4 the meteorological effects could not be separated from the effect of sound source directivity during these 10 months. A more complete analyze will be done on two years of data. The sound level for small sound speed gradients (e.g. crosswind) is much lower than for both large positive and large negative sound speed gradients. For moderate downward refraction the ground attenuation could be minor even with snow present, otherwise the sound levels are lower for snow cover, both for large negative and positive sound speed gradients. This indicates that ground attenuation and refraction are closely linked and could hardly be separated.

Sound from wind turbines is therefore strongly dependent on the present meteorological situation. We have seen large variations at 1000 m but very small if any at 400 m. By and large we can conclude that the meteorological conditions must be taken into consideration starting at distances somewhere between 400 and 1000 m. Lower sound levels are found during the winter, for the Dragaliden site in figure 3, and especially after snowfall when both ground and trees are covered with porous snow. It is noticeable that the meteorological conditions introduce mean variations of 6 - 14 dBA even for these high-elevated wind turbine sources. It could be concluded that the variation in sound level due to different weather conditions is almost of the same order for a distant high-elevated sound source as for a nearer placed source close to the ground.

3.3 Amplitude modulation

Sound from the wind turbine blades is amplitude modulated and often described as a “swish” sound. Sudden changes in the sound from the wind turbines and the interference pattern have been reported². A method using fast Fourier transform that detects amplitude modulation from wind turbines are used³.

Sound measurements have been performed 8 times/s with time weighting fast to study amplitude modulation, AM. The continuous sound measurements are divided in 15 s long periods and each time frame is analyzed. Observations at the sites and studies of different amplitude modulation spectra has resulted in a definition for amplitude modulation for our sites:

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

Figure 5 shows the sound level and RMS-value from the Dragaliden site during a case study at a distance of 2.4-3.7 km from the wind turbines during day and night.

The case in figure 6 shows the same pattern, much larger peak-to-peak values at the imission point than at the emission point for the same time which indicate that the enhanced AM sound is influenced by the propagation path or the interference between several wind turbines rather than changes in the emitted sound.

Continuous measurements of the sound pressure level were recorded 8 times/s between 18 August and 1 October 2011 for the Ryningsnäs and the Dragaliden sites. Figure 7 and 8 display how often AM sound occurred at the different stations by dividing into different wind direction, sound speed gradient, turbulence intensity and time. Note that AM percent is given as AM time divided by the total time for the actual bin. The wind turbines at Ryningsnäs, see figure 7, is at 400 and 600 m distance. More AM is found during precise downwind conditions (285 and 250°) but also during precise upwind conditions. The sound speed gradient is calculated along a line between the wind turbines.

The wind turbines at Dragaliden, see figure 8, is located 1-2 km (170 - 260°) from the long-term measuring station. Due to the longer distance at the Dragaliden site few upwind conditions

show AM sound. The turbulence intensity (standard deviation of wind speed divided by the mean wind speed during 10 minutes) influences the rate of AM. High turbulence intensity at hub height decreases the occurrence of AM sound. For both sites the occurrence of AM sound increases during evening, night and morning and then decreases during the day. This pattern follows perfectly how the temperature inversion is built up during the evening and nights and breaks up from ground when the rising sun heats the ground. For a specific wind direction we can get AM sound between 30 - 40 % of the time. The total time for AM sound for the Ryningsnäs and Dragaliden site is 27 and 11 % respectively.

4 DISCUSSION AND CONCLUSIONS

Sound from wind turbines is strongly dependent on the meteorological situation. The effect increases with distance. For 12 wind turbines at 1 - 2 km a meteorological variation of 6 - 14 dBA were found depending on ground conditions and refraction. For 2 wind turbines at 400 - 600 m the first analyze during these 10 months the meteorological effect could not be separated during these with from the directivity of the source.

The lowest sound levels are found for negative sound speed gradients (upward bending sound waves) when the sound wave touches the ground and large ground attenuation occur. It shows the strong coupling between refraction and ground attenuation. The ground attenuation and refraction are closely linked and could hardly be separated. Lower sound levels are found during the winter with snow on the ground. Especially after snowfall when the snow is porous and the tree branches are covered by snow.

Amplitude modulated sound from wind turbines is an effect of both meteorology and acoustics and are observed during roughly 30 % of the time at 400 m and 10 % of the time at 1 km from the closest turbine. AM sound is influenced by conditions in the propagation path and interference pattern can occur. It is most common in the evening, night and morning when the turbulence intensity is low.

5 ACKNOWLEDGEMENTS

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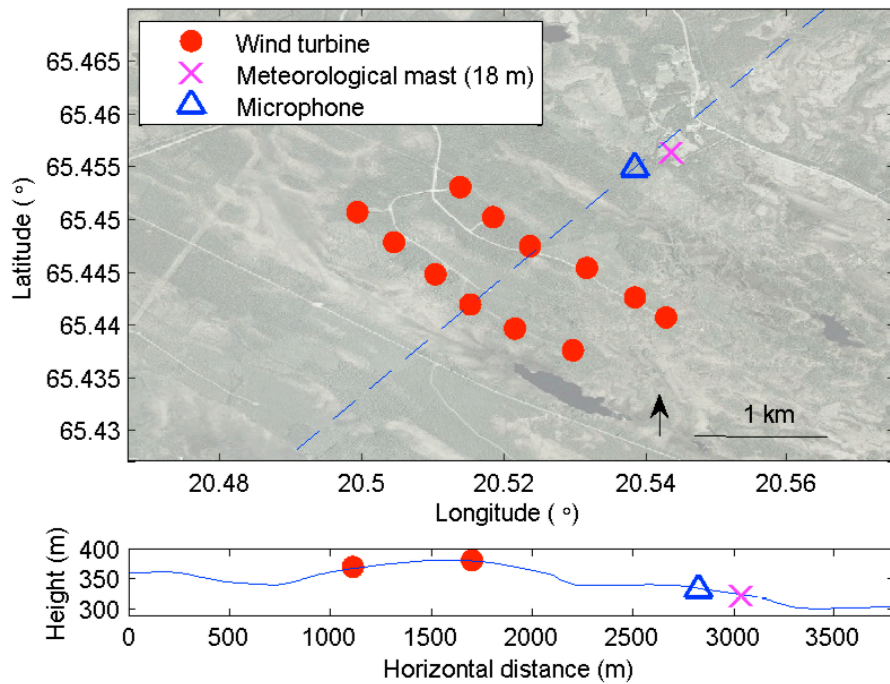


Fig. 1. Map of the Dragaliden site (courtesy to Google Earth). Sound speed gradients for this site are calculated along the dashed line throughout this paper. Positive direction is to the northeast. The height contour along the dashed line from southwest to northeast is shown below.

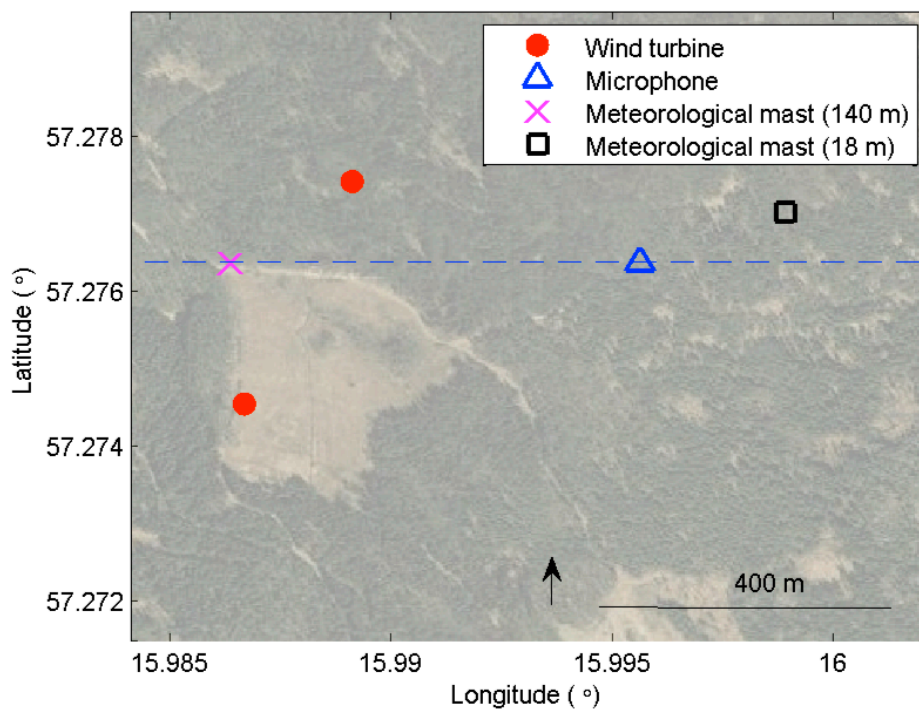


Fig. 2. Map of the Ryningsnäs site (courtesy to Google Earth). Sound speed gradients for this site are calculated along the dashed line throughout this paper. Positive direction is to the east.

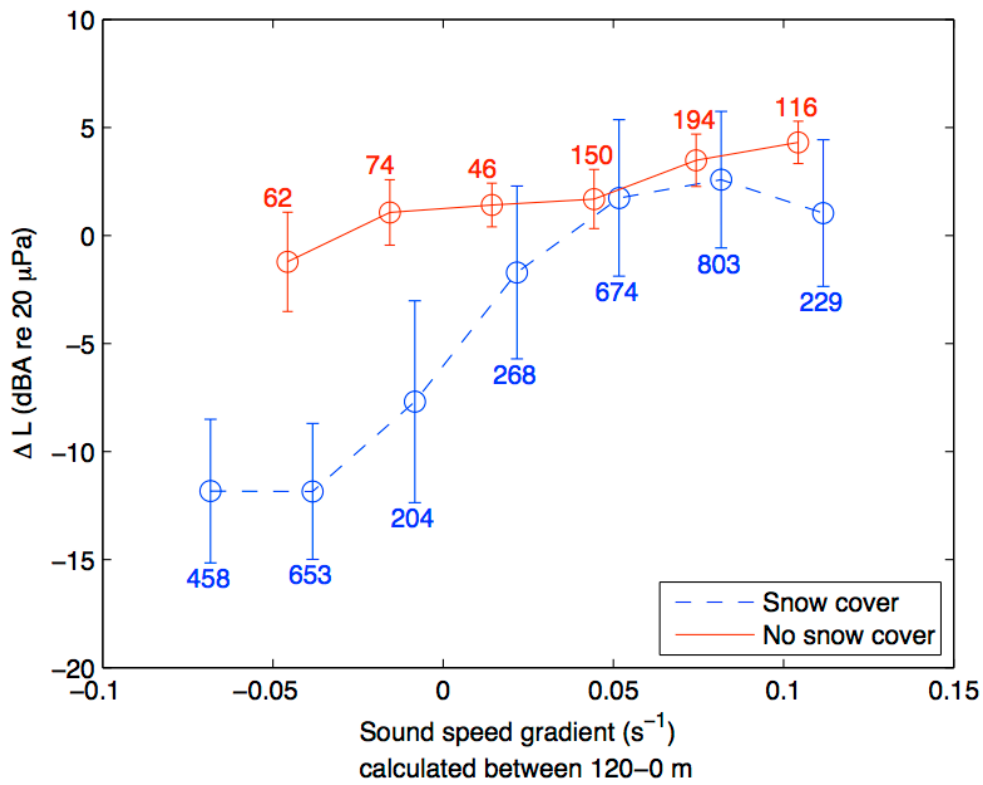


Fig. 3. Relative sound pressure level corrected for atmospheric absorption during different sound speed gradient at 1 km distance from the Dragaliden wind turbine site with and without snow cover during 10 months.

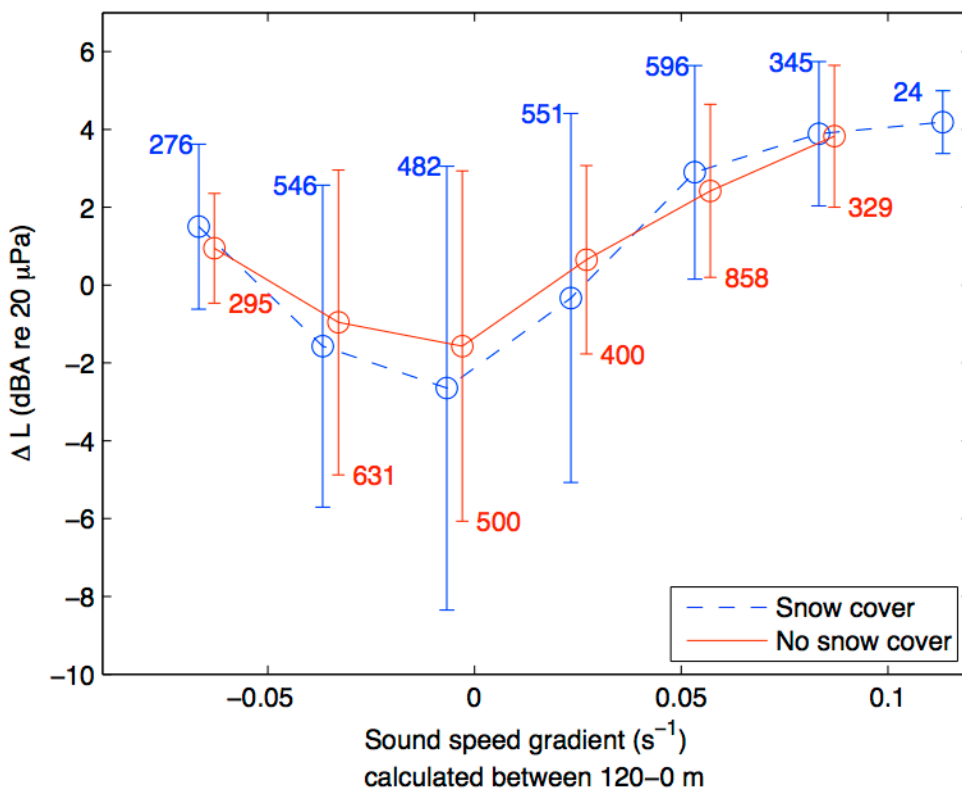


Fig. 4. Relative sound pressure level corrected for atmospheric absorption during different sound speed gradient at 400 m distance from the Ryningsnäs wind turbine site with and without snow cover during 10 months.

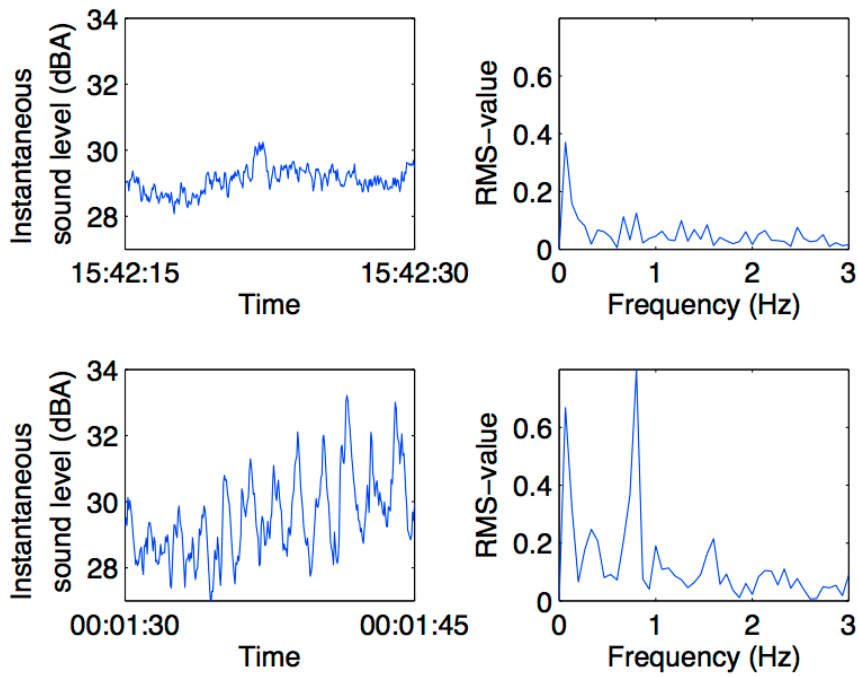


Fig. 5. Sound measurements from the Dragaliden site on 20 July 2011. Instantaneous sound level and corresponding RMS-value is shown for two 15 s long periods during day and night.

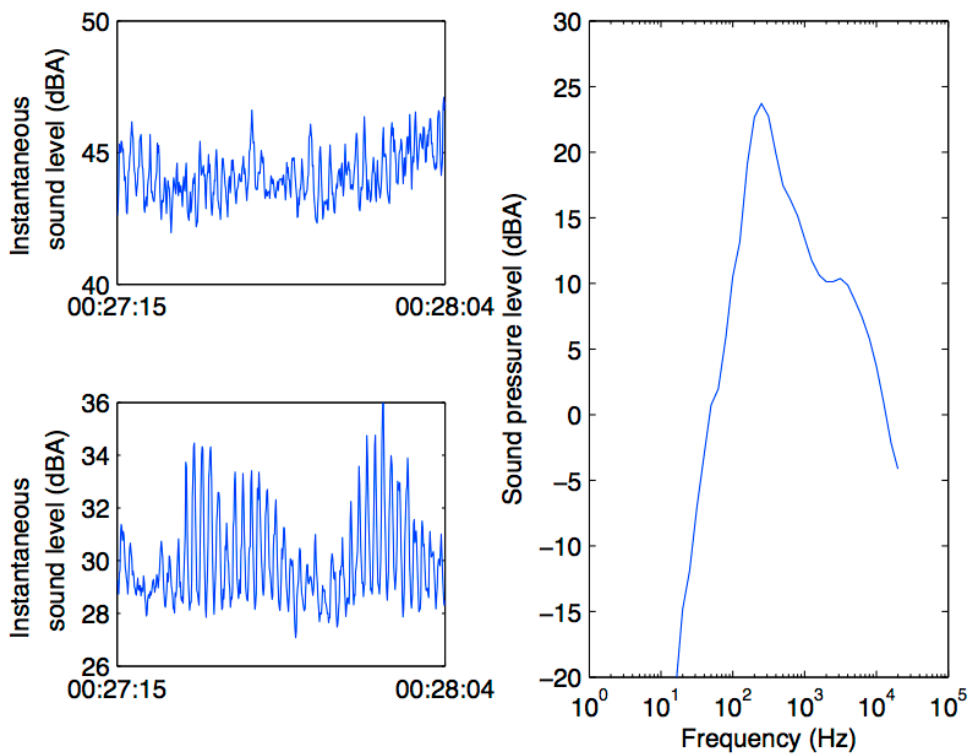


Fig. 6. Simultaneous sound level measurements close and 3-4 km from the wind turbines at the Dragaliden site. The emission sound spectrum is also given.

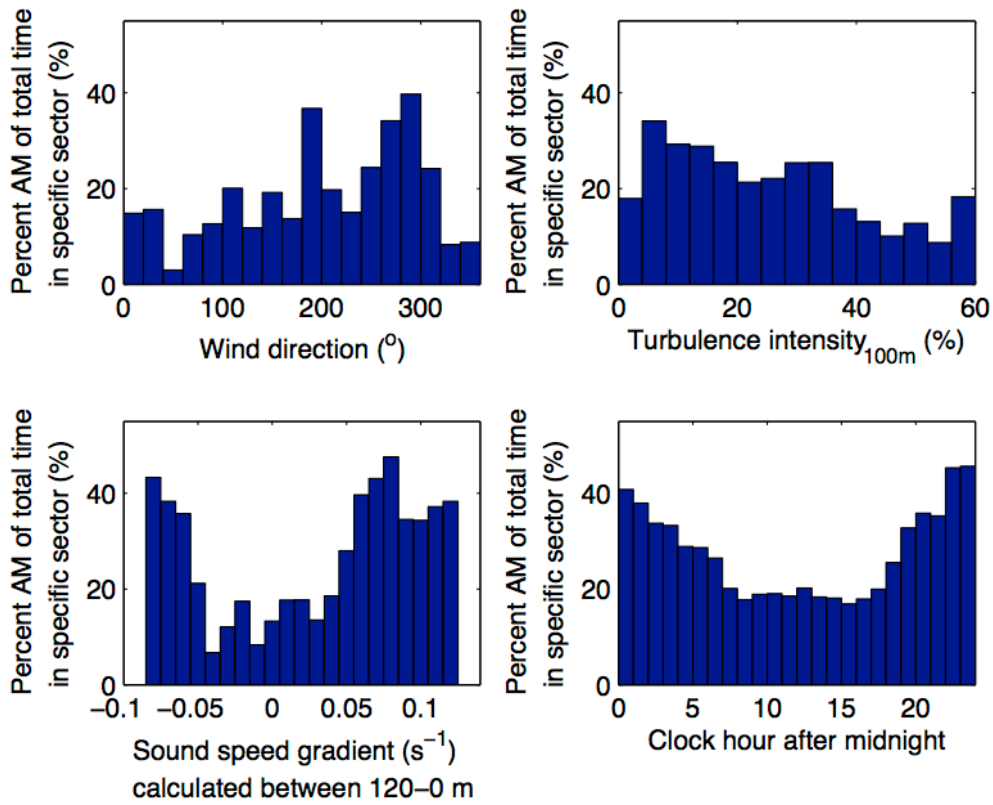


Fig. 7. Percent of AM for various parameters at the Ryningsnäs site for the actual bin.

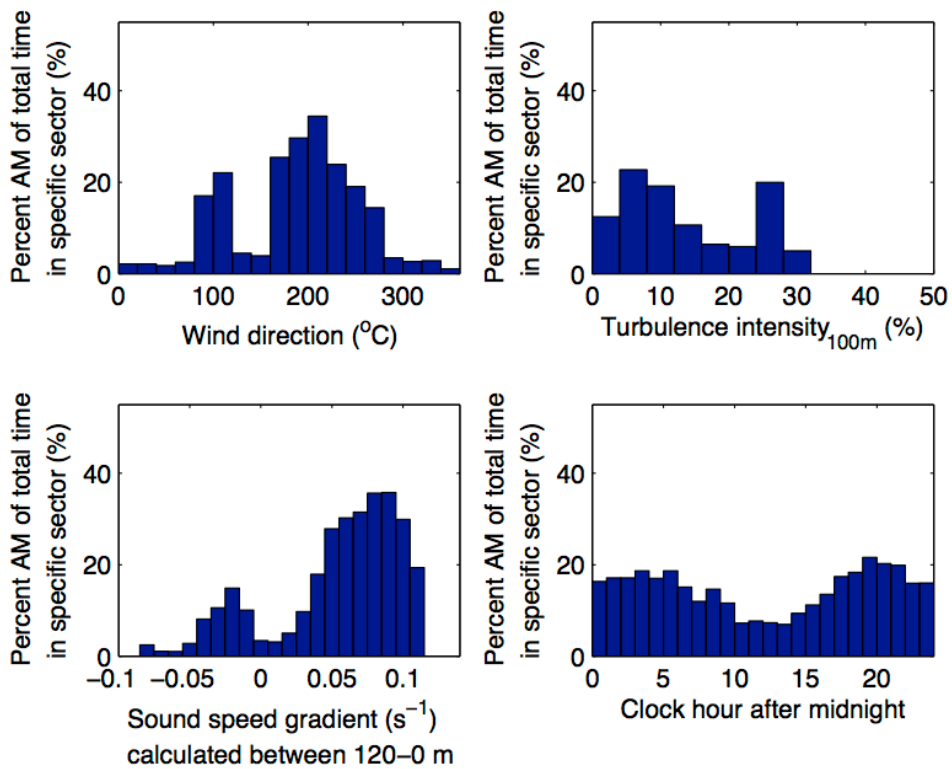


Figure 8. Percent of AM for various parameters at the Dragaliden site for the actual bin.