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Low-level wind maxima and their effect on wind turbine sound

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Summary

Refraction is an important factor for sound propagation from wind turbines. The simplified concept for the effects of refraction based on the logarithmic wind profile or other approaches where the wind speed is continuously increasing with height, is often not applicable in cold climates. The stably stratified boundary layer often features low-level wind maxima. This study was performed to analyse the effect of wind maxima below hub height on sound propagating from wind turbines. Long-term meteorological measurements in the vicinity of a wind farm in northern Sweden are used to identify low-level wind maxima. To analyse the effect of low-level wind maxima on sound propagation, sound measurements were conducted simultaneously to the meteorological measurements.

1. Introduction

Outdoor sound propagation, as wind turbine (WT) sound, is affected by meteorological conditions. One of the most important meteorological effects is refraction [6]. Refraction mainly occurs due to

wind speed and temperature gradients and is characterised by the bending of the path of a sound ray towards regions of lower effective sound speed. A simplified concept illustrates the refraction pattern due to vertical wind speed gradients [e.g., 5, 6, 8]: refraction leads to downward bending and higher sound levels downwind of a sound source, and upwind of a sound source, upward bending occurs and results in lower sound levels (Fig. 1a). However, the stably stratified atmospheric boundary layer (SBL) is a common feature in cold climates and makes this simplified concept unapplicable. In the SBL, low-level wind maxima (LLWM) are often present. The reasons for the formation of LLWM are manifold [e.g., 7, 10].

LLWM above the WTs hub height were shown to increase the effect of downward refraction [1, 4, 9]. The maximum in wind speed above the sound source traps the sound waves between the LLWM and the surface, and therefore increases the level of WT sound near the surface at a distance much greater than the altitude of the LLWM [2].

LLWM can also occur below hub height, especially in very stable conditions. In the light of the ongoing development towards higher WTs, the probability for LLWM increases. Since in this case, the sound source is above the LLWM, a complete or partial trapping of the sound waves above the LLWM can be expected (Fig. 1b), which is contrary to the situation discussed above. Therefore, lower levels of WT sound close to the surface are assumed for downwind conditions. In order to test this assumption, long-term meteorological and acoustic measurements have been conducted in the vicinity of a wind farm in northern Sweden.

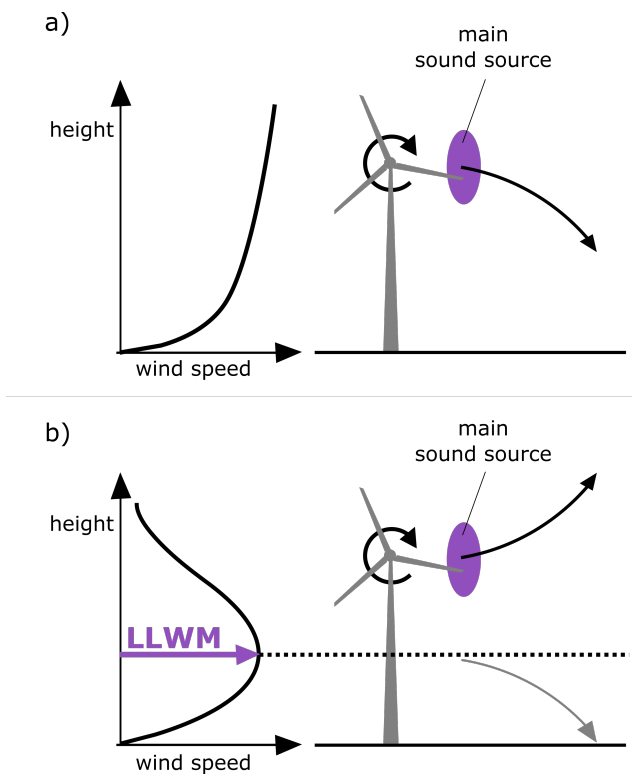

Fig. 1 Schematic illustration of the refraction patterns downwind of a wind turbine for a) a logarithmic wind profile and b) a low-level wind maxima (LLWM) below hub height [based on 3].

2. Measurements

Between August 2016 and June 2017, measurements were conducted in the vicinity of a wind farm in northern Sweden (Fig. 2). The surrounding landscape is undulating with hills and ridges up to $600\,\mathrm{m}$ above sea level. The sparsely populated area is predominantly covered by forests but several rivers, streams and lakes can also be found. An acoustic station was installed in a forest approximately $200\,\mathrm{m}$ away from the closest houses of a small settlement and ca. $500\,\mathrm{m}$ from a road, which bears little traffic. The wind farm is located in the northwest direction of the acoustic station on Nådagubbliden, which is a ridge with maximum elevations of 460 to $510\,\mathrm{m}$ above sea level. The wind farm consists of 22 Vestas V90 (2 MW) WTs with a hub height of $105\,\mathrm{m}$. Meteorological measurements were conducted on a mast approximately $100\,\mathrm{m}$ southeast of the acoustic station and on a meteorological tower, close to the centre of the wind farm.

Wind speed and direction were measured at $1.3\,\mathrm{m}$, $2.3\,\mathrm{m}$ and $4.6\,\mathrm{m}$ above the snow-free ground on a meteorological mast, which was placed in the middle of a field. The closest buildings and higher vegetation, i.e., trees and bushes, were around $50\,\mathrm{m}$ away to ensure as undisturbed measurement conditions as possible. Additionally, wind measurements at $60\,\mathrm{m}$, $85.5\,\mathrm{m}$, and $105\,\mathrm{m}$ at a meteorological tower were provided by the operator of the wind farm. 10-min averages of the equivalent sound pressure level, L_{Aeq}, were collected using a Norsonic NOR140 sound level meter and a Nor1214 outdoor microphone equipped with a rain hood and a dust mesh. The microphone was mounted $1.5\,\mathrm{m}$ above the snow-free ground. Simultaneous with the meteorological and the acoustic measurements, the wind farm operator provided 10-min averages of the rotational frequency of each wind turbine. All measurements were averaged over the same 10-min intervals.

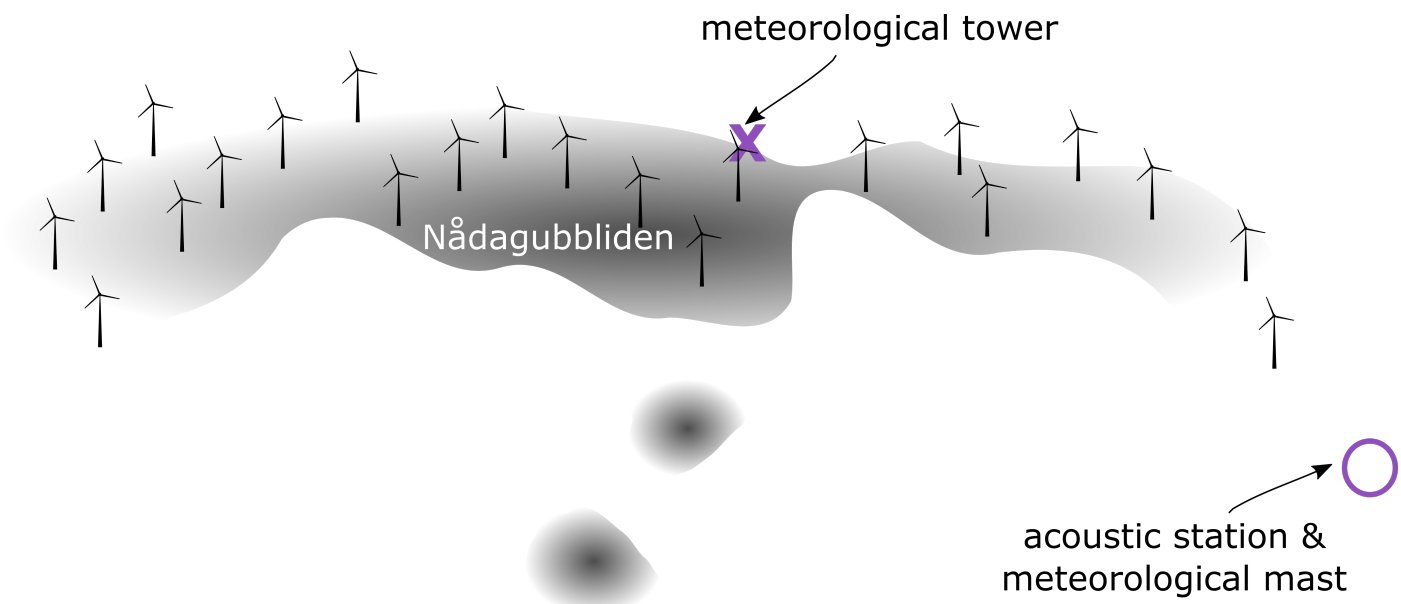

Fig. 2 Schematic illustration of the measuring site with the acoustic station and the meteorological mast (circle) and the meteorological tower (x).

3. Methods

Two types of LLWM have been chosen to analyse their effect on WT sound:

- **Type I**: wind speed is greatest at $85.5\,\mathrm{m}$, second greatest at $105\,\mathrm{m}$ (hub height), and lowest at $60\,\mathrm{m}$ (tip of the lowermost blade) and
- **Type II**: wind speed is greatest at $85.5\,\mathrm{m}$, second greatest at $60\,\mathrm{m}$ (tip of the lowermost blade), and lowest at $105\,\mathrm{m}$ (hub height).

Type I was expected to has a smaller effect on WT sound than Type II due to the stronger wind speed gradient between $85.5\,\mathrm{m}$ and $105\,\mathrm{m}$ for Type II. Two minimum differences, Δu, between the largest and second largest wind speed are chosen to analyse the impact of the strength of a LLWM: $\Delta u = 0.2\,\mathrm{m\,s^{-1}}$ and $\Delta u = 0.5\,\mathrm{m\,s^{-1}}$. Note that acoustic data was only selected for further analyses if the median of the rotational frequency of all WTs, RF, was $\geq 14.0\,\mathrm{rpm}$. This criterion was applied to ensure that WT sound was possible to be detected at the acoustic station if no LLWM below hub height was present.

4. Results and discussion

The occurrence of L_{Aeq} for occasions without LLWM and with LLWM (Type I or Type II) for downwind conditions and $RF \geq 14.0\,\mathrm{rpm}$ are shown in Figure 3, where a) shows LLWM meeting $\Delta u = 0.2\,\mathrm{m\,s^{-1}}$ and b) shows LLWM with an increased strength ($\Delta u = 0.5\,\mathrm{m\,s^{-1}}$). Compared to occurrences without LLWM, Type I mainly increases the occurrence of $L_{Aeq} < 32\,\mathrm{dBA}$, while Type II increases the occurrence of $L_{Aeq} \approx 27\,\mathrm{dBA}$ (Fig. 3a). $L_{Aeq} > 40\,\mathrm{dBA}$ seldom occur for either of the LLWM types. For LLWM with an increased strength ($\Delta u = 0.5\,\mathrm{m\,s^{-1}}$, Fig. 3b), the effect of LLWM on L_{Aeq} increases, especially for Type I.

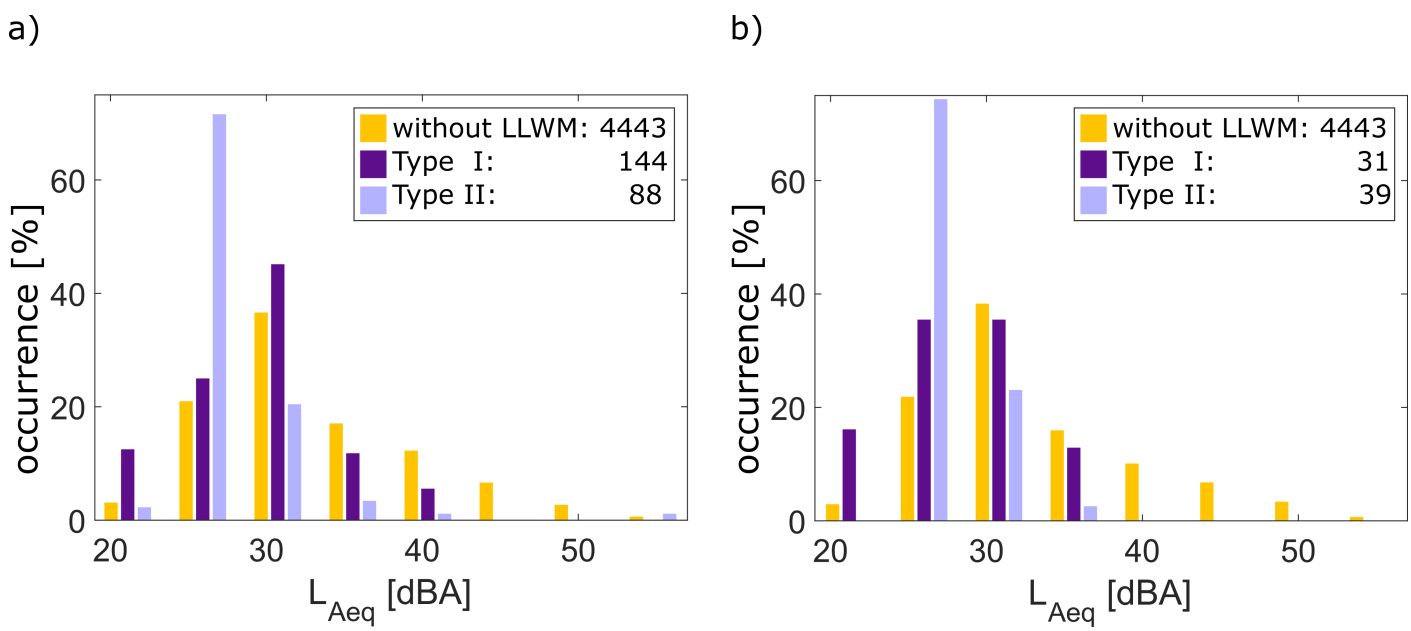

Fig. 3 Occurrence of L_{Aeq} for occasions without LLWM and with LLWM – Type I or Type II – for downwind conditions, $RF \geq 14.0\,\mathrm{rpm}$ and a) $\Delta u = 0.2\,\mathrm{m\,s^{-1}}$ or b) $\Delta u = 0.5\,\mathrm{m\,s^{-1}}$ [based on 3]. The numbers in the legends refer to the amount of data of each category.

The more pronounced effect of Type II compared to Type I can be explained by the definition of the

two LLWM types. For Type II, the wind speed at the uppermost level is the lowest of the three levels, therefore, the gradient between the two highest levels is presumably larger than the one for Type I. Thus, more effective upward refraction is caused, leading to a more effective trapping of WT sound above the LLWM.

5. Conclusions

Analyses of long-term acoustic and meteorological measurements in northern Sweden indicate that LLWM below hub height reduce WT sound in the downwind direction. The effect is larger if stronger LLWM ($\Delta u = 0.5\,\mathrm{m\,s^{-1}}$) are present. Both LLWM types lead to lower L_{Aeq} when compared to occurrences without LLWM. The effect is larger if the lowest of the three wind speeds was measured at the uppermost level (Type II), which can be related to a more effective upward refraction above the LLWM. Since LLWM decrease the WT sound close to the surface in the downwind direction, the occurrence of LLWM can improve the conditions for residents. Furthermore, an increase in the height of the WTs at this site would increase the potential of LLWM below hub height.

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