Received: 24 April 2019 | Revised: 1 March 2020 | Accepted: 2 April 2020
DOI: 10.1002/we.2517

WILEY

SHORT COMMUNICATION

Impact of low-level wind maxima below hub height on wind turbine sound propagation

Kristina Conrady[1] | Karl Bolin[2] | Anna Sjöblom[1] | Anna Rutgersson[1]

[1]Department of Earth Sciences, Uppsala University, Uppsala, Sweden
[2]Marcus Wallenberg Laboratory, Kungliga Tekniska Högskolan, Stockholm, Sweden

Correspondence
Kristina Conrady, Department of Earth Sciences, Uppsala University, Villavägen 16, 75236 Uppsala, Sweden.
Email: kristina.conrady@geo.uu.se

Funding information
Swedish Energy Agency, Grant/Award Number: 40969-1 and 44948-1

Abstract

An analysis of the effect of low-level wind maxima (LLWM) below hub height on sound propagating from wind turbines has been performed at a site in northern Sweden. The stably stratified boundary layer, which is typical for cold climates, commonly features LLWM. 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 there. Long-term meteorological measurements in the vicinity of a wind farm were therefore used to identify LLWM. Sound measurements were conducted simultaneously to the meteorological measurements. LLWM below hub height decrease the sound level close to the surface downwind of the wind farm. This effect increases with increasing strength of the LLWM. The occurrence of LLWM as well as strength and height of the LLWM are dependent on the wind direction.

KEYWORDS

atmospheric acoustics, low-level wind maxima, wind energy, wind turbine sound

1 | INTRODUCTION

Although the general public opinion is positive towards wind farms,[1] nearby residents are often affected by both visual impact and sound.[2,3] Guidelines for wind turbine (WT) sound are therefore present in most countries. The sound generated by WTs is affected by processes in the atmosphere as well as atmospheric conditions. Refraction is one of the most significant meteorological effects on sound propagation, aside from atmospheric absorption and scattering by turbulence.[4,5] Refraction can be described as bending of the propagation path due to gradients of the effective sound speed and depends mainly on vertical wind speed gradients and temperature gradients along the propagation path. Usually, the impact of wind speed gradients outweigh the impact of temperature gradients. To illustrate the impact of refraction due to wind speed gradients, a simplified concept has commonly been assumed: due to a continuously increasing wind speed with height, downward refraction occurs downwind of a sound source (Figure 1A) while upward refraction occurs upwind of a sound source (e.g., other studies[4-6]). That leads to higher sound levels in the downwind direction and lower sound levels in the upwind direction. This simplified concept is, however, often not applicable in cold climates, where the stably stratified atmospheric boundary layer (SBL) is a common feature. In the SBL, low-level wind maxima (LLWM) are often present. The reasons for the formation of LLWM are manifold. For example, processes that can cause LLWM and are possible in hilly terrain are, for example, inertial oscillations (e.g., Andreas et al[7]), baroclinicity due to sloping terrain (e.g., Tuononen et al[8]), and katabatic winds (e.g., Renfrew and Anderson [9]).

Most of the current research on LLWM has been focused on LLWM *above* hub height. LLWM above the WTs hub height increase the effect of downward refraction. The sound waves are then trapped between the LLWM and the surface and therefore increase the level of WT sound near the surface at a distance $r \gg H$, where r is the horizontal distance from the WT and H is the altitude of the LLWM.[10] Makarewicz[11] investigated the impact of downward refraction due to LLWM on sound propagating from elevated sound sources. A ray-tracing approach was used to describe sound propagation of a sound source located below the LLWM. For offshore WTs, Johansson[12] computed sound propagating

The peer review history for this article is available at https://publons.com/publon/10.1002/we.2517.

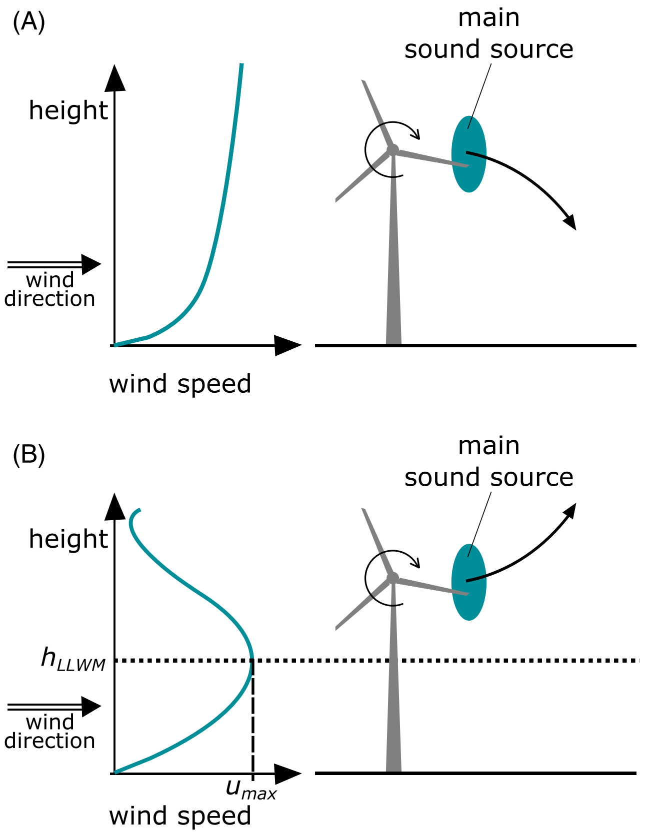

FIGURE 1 Schematic illustration of the refraction patterns downwind of a wind turbine for (A) a logarithmic wind profile and (B) a low-level wind maxima (LLWM) below hub height. h_{LLWM} is the height and u_{max} the maximum wind speed of the LLWM [Colour figure can be viewed at wileyonlinelibrary.com]

from a source at 65 m above the sea level, while the LLWM was at an altitude of 200 m and higher. Törnblom[13] measured sound levels from a source mounted at a height of 36 m during meteorological conditions with LLWM above 100 m. In all three studies, the sources were well below the LLWM, which explains the trapping of sound waves below the LLWM. Furthermore, the focus was on sound propagation offshore. The impact of LLWM on sound propagating around offshore WTs is then seen as a channelling effect downwind of the sound source that leads to a higher sound pressure level (SPL) near the surface (see also Bolin et al[14]). In calm conditions, the sea surface has a high impedance (i.e., a high reflectance), which amplifies the effect of channelling, and it may not be the same over a land surface. For onshore conditions, numerous authors (e.g., other studies[15,16]) have been using different source models coupled to calculations of sound propagation without focusing on occasions with LLWM. WT sound for LLWM above hub height has explicitly been calculated by Makarewicz et al. [17]

However, in very stable conditions, LLWM often occurs *below* hub height and the ongoing development towards higher hub heights further increases their probability. LLWM below hub height will then instead lead to a complete or partial trapping of the sound waves from a WT above the LLWM (Figure 1B). Hence, this should result in lower levels of WT sound close to the surface in the downwind direction, thereby making the conditions for residents nearby much more favourable. To test this hypothesis, long-term meteorological and acoustic measurements have been conducted in the vicinity of a wind farm in northern Sweden. A separation into different types of LLWM is made and possible effects on the SPL are analysed.

2 | MEASUREMENTS

2.1 | Measuring site

Measurements were conducted close to Nåda, a settlement in the Malå municipality, northern Sweden (65.09°N, 18.87°E) (Figure 2) between October 2016 and June 2017. A hilly landscape surrounds the measuring site, with hills and ridges up to 600 m a.s.l. and is predominantly covered by forests. In this sparsely populated area, several rivers, streams, and lakes can be found. Nåda is surrounded by a road in the east and south direction that is not frequently used. The acoustic station was set up ca. 200 m away from the closest houses and ca. 500 m from the road. To the northwest of the acoustic station, Nådagubbliden is located, which is a ridge with maximum elevations of 460 to 510 m a.s.l. On Nådagubbliden, 22 Vestas V90 (2 MW) WTs with a hub height of 105 m are situated. The calculated sound level at the location of the acoustic station is below 35 dBA. Meteorological measurements were conducted on a mast approximately 100 m southeast of the acoustic station and on a tower, close to WT15. The distance between the tower and the mast/the acoustic station is approximately 5 km.

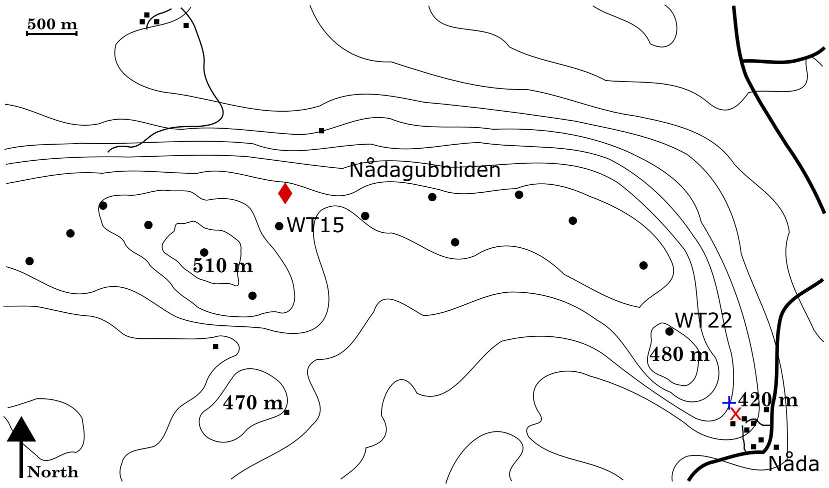

FIGURE 2 The measuring site with the 14 closest wind turbines (black dots), meteorological tower (red rhombus), acoustic station (blue +), meteorological mast (red cross), large roads (bold lines), small roads (dotted lines), and houses (black squares). The distance between the isohypses is 20 m; the numbers indicate the height above sea level [Colour figure can be viewed at wileyonlinelibrary.com]

2.2 | Meteorological measurements

A meteorological mast was installed to measure the wind speed at 1.3 m, 2.3 m, and 4.6 m above the snow-free surface. The mast was placed in the middle of a field, around 50 m from the closest buildings, trees, and bushes, to ensure as undisturbed measurement conditions as possible. Further, wind measurements (speed and direction) at 60 m, 82.5 m, and 105 m at a meteorological tower close to WT15 (see Figure 2) were provided by the operator of the wind farm. The meteorological measurements were averaged over 10 min.

2.3 | Acoustic measurements

The acoustic station was placed in a forest and consists of 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 m above the snow-free ground. Due to a snow depth of up to 90 cm, the distance between the microphone and the ground decreased for several months. 10-min averages of the equivalent SPL L_{Aeq} were collected. The acoustic measurements were conducted simultaneous with the meteorological measurements.

2.4 | Operational data of WTs

The operational data provided by the wind farm operator includes 10-min averages of rotational frequency of each WT. Here, the median is used, hereinafter referred to as *RF*. The provided operational data is simultaneous with the meteorological and the acoustic measurements.

3 | METHODS

3.1 | Types of low-level wind maxima

All LLWM analysed here are located between altitudes of 60 and 105 m. LLWM, which occur below 60 m or above 105 m, are not captured by the measurements. The LLWM are divided into four groups and defined as (Figure 3):

- Type I_a:$u_{60} > u_{105} + \Delta u$ and $u_{105} > u_{82.5}$,
- Type I_b: $u_{60} > u_{82.5} + \Delta u$ and $u_{82.5} > u_{105}$,
- Type II_a: $u_{82.5} > u_{105} + \Delta u$ and $u_{105} > u_{60}$,
- Type II_b: $u_{82.5} > u_{60} + \Delta u$ and $u_{60} > u_{105}$,

where u is the wind speed (m s^{-1}) and the indices $_{60}$, $_{82.5}$, and $_{105}$ refer to the measuring height (m) on the meteorological tower. Δu is the minimum difference between the highest and the second highest wind speed of u_{60}, $u_{82.5}$, and u_{105}, that is, Δu indicates the minimum strength of the LLWM. This means that the highest wind speed of Type I_a and Type I_b is measured at a height of 60 m, thus the LLWM is situated below 82.5 m. The potential height for the LLWM described by the other two types, Type II_a and Type II_b, is then situated between 60 m and 105 m. For Type I_b and Type II_b, u_{105} is the lowest of the three wind speeds; hence, the wind speed is decreasing towards the height of 105 m (hub height), resulting in a wind soeed even lower than u_{60}. Therefore, a more efficient upward refraction is assumed (Figure 1). Thus, Type I_b and Type II_b may lead to more effective trapping than Type I_a and Type II_a. However, the wind maximum of Type I_a and Type I_b is measured at the same height as the tips of the rotor blade reach in their lowermost position (i.e., 60 m). Since this is therefore below the estimated location of the maximum of the main sound source, which is located in an area around the hub height,[18] it is less likely that sound propagates towards the surface for Type I_a and Type I_b than for Type II_a and Type II_b, which have their maximum within the area of the main source.

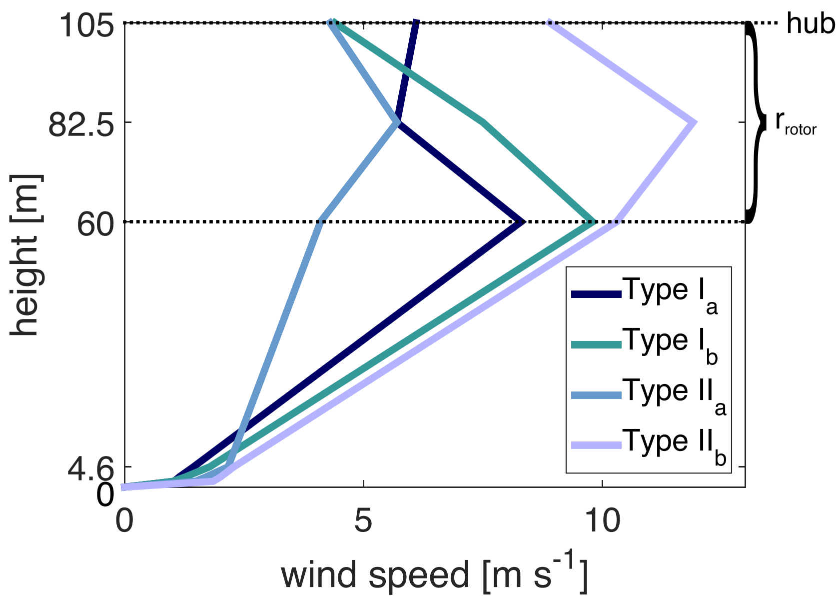

FIGURE 3 Examples of wind speed profiles with low-level wind maxima (LLWM) classified as Type I_a, Type I_b, Type II_a, and Type II_b, where hub indicates the hub height and r_{rotor} is the radius of the rotor [Colour figure can be viewed at wileyonlinelibrary.com]

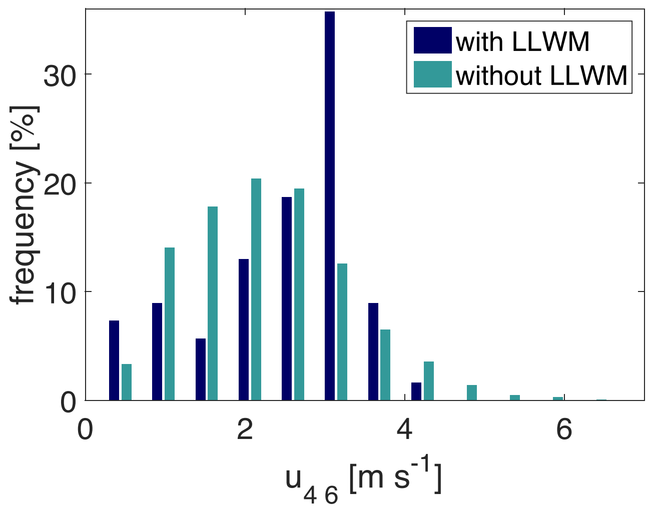

FIGURE 4 Frequency distribution of wind speed at 4.6 m for $RF \geq 14.0$ rpm and $\Delta u = 0.5$ m s^{-1} for occasions with and without low-level wind maxima (LLWM) [Colour figure can be viewed at wileyonlinelibrary.com]

LLWM detected at the meteorological mast located below heights of 4.6 m (the highest measuring level at the mast) are not analysed. Those LLWM are features of drainage flow, which is a down-slope directed flow of cold air, and also common in SBL in hilly and mountainous terrain. Their maximum wind speed is usually lower than the wind speed at 60 m, 82.5 m, and 105 m and are assumed to have a minor effect on sound propagating from the WTs.

3.2 | Selection criteria for sound measurements

The selection criteria for the sound measurements are $RF \geq 14.0$ rpm and that downwind conditions (i.e., 249° to 359°) are used exclusively. These two criteria should ensure that sufficiently high sound levels are generated by the WTs to potentially be detected at the receiver if no LLWM or other circumstances, for example, snow on the ground and the vegetation,[19] prevent that. More comprehensive selection techniques were not applied. For example, criteria used in Conrady et al[20], such as spectral resemblance or occurrence of amplitude modulation, would prevent cases where the WT sound was trapped above the LLWM to go through the selection process, and since these cases are here crucial, a similar procedure could not be applied. However, LLWM occur in meteorological conditions that can be different from those without LLWM, and hence, differences in wind conditions are conceivable. Since the wind speed impacts the sound in the vegetation and on the microphone, frequency distributions of the wind speed at 4.6 m for occasions with and without LLWM were compared (Figure 4). No clear difference can be seen, and no assumption that wind-induced sound is more common or higher for one of the situations can be made. Furthermore, there is no indication that other ambient sound sources are more pronounced for either occasions.

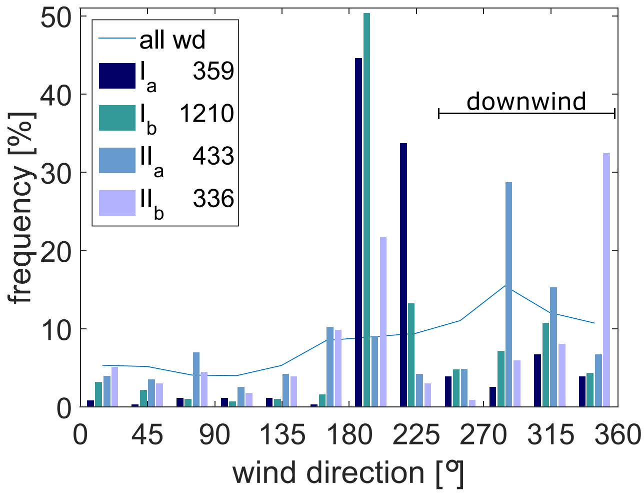

FIGURE 5 Frequency distribution of wind directions at 82.5 m for all measurements (line) and for the four low-level wind maxima (LLWM) types (bars). The difference between maximum wind speed and the second largest wind speed is at least 0.2 m s^{-1} (Δu = 0.2 m s^{-1}). The numbers in the legend refer to the amount of 10-min averages [Colour figure can be viewed at wileyonlinelibrary.com]

4 | RESULTS AND DISCUSSION

4.1 | Occurrence of LLWM

The most common wind directions at 82.5 m for all measurements were between 255° (WSW) and 315° (NW) (Figure 5). However, the dominant wind direction usually is southwest (ca. 230°) at these latitudes. This difference between the large scale and the local wind can be explained by the air being steered around the top of a hill, located southwest of the meteorological tower. Especially in stable conditions, hills and mountains commonly have this channelling effect on the flow. The least common wind directions were between 15° (NNE) and 45° (NE), which is the same for large-scale conditions at these latitudes.

As much as 45% of Type I_a and 55% of Type I_b occur for wind directions between 180° and 210°. Wind directions between 210° and 240° coincide with 34% of Type I_a and 13% of Type I_b. Two hills located in the sector around 200° are therefore assumed to affect, or cause, the formation of these two types of LLWM. A combination of warm air advection and topographical effects is therefore likely. The formation of Type II_a and Type II_b cannot be explained by a topographical cause, as both types mainly occur for wind directions that cannot be related to a topographical feature causing LLWM. Almost 50% of Type II_a occurs for wind directions between 270° and 330° and Type II_b most often (32%) for wind directions between 330° and 360°. 180° to 210° are also common wind directions (22%) for Type II_b, where advection of colder air masses might be the main driver.

LLWM are uncommon for wind directions between 240° and 270° (82.5 m), which can be explained by a hill in the sector, 40 m higher than the base of the meteorological tower. Instead of going around this hill, the flow is accelerated over it, and leads to a LLWM, especially in stable conditions. However, these LLWM were not detected by the tower because they occur in altitudes above the uppermost measuring level. Depending on the characteristics of the flow over the hill, LLWM can also occur between 4.6 and 60 m. However, LLWM at these altitudes were also not detected here because no measurements were made for this altitude range.

Looking at all wind directions, LLWM with Δu = 0.2 m s^{-1} were observed in 11.1% of the measurements, while LLWM with Δu = 0.5 m s^{-1} were observed in 6.8% (Table 1). Taking the criterion of *RF* into account, this number reduces to 8.5% for Δu = 0.2 m s^{-1} and to 5.5% for Δu = 0.5 m s^{-1}. Type I_b is the most common type of LLWM, independent of the chosen Δu and *RF*. If the *RF* criterion is not applied, around 50% of Type I_a and Type I_b with Δu = 0.2 m s^{-1} also meet the requirement Δu = 0.5 m s^{-1}. For Type II_a and Type II_b, that fraction is only 20% and 40%, respectively. Thus, the difference between the maximum wind speed and the second largest wind speed is usually larger for Type I_a and Type I_b than for Type II_a and Type II_b if all measurements are taken into account, also those with $RF < 14$ rpm. For $RF \geq 14$ rpm, the occurrence of stronger LLWM (Δu = 0.5 m s^{-1}) of Type I_b is 75%. That means Type I_b is tendentially stronger for high *RF*. This, in combination with the high occurrence of Type I_b for southerly winds, can indicate the impact of a wake effect in upwind direction of the meteorological tower. In the wake of a WT, the wind speed around hub height can be reduced while it can be less affected towards the tips of the rotor blades. However, this does not not affect the analyses since only downwind conditions are used, and the meteorological tower is hence not likely to be in such a wake.

4.2 | Impact of LLWM

Figure 6 shows the frequency (%) as a function of L_{Aeq} for occasions with and without LLWM for Δu = 0.2 m s^{-1} (Figure 6A) and Δu = 0.5 m s^{-1} (Figure 6B). Both frequency distributions are skewed to larger L_{Aeq}. The maximum for occasions with LLWM is shifted towards lower L_{Aeq} compared with the maximum of the distribution for occasions without LLWM. The frequency of lower L_{Aeq} is increased if LLWM were observed, while higher L_{Aeq} occur either less often or do not occur at all. If Δu = 0.2 m s^{-1}, that is, the strength of the LLWM is increased to 0.5 m s^{-1}, the maximum of the frequency distribution for occasions with LLWM is shifted towards lower L_{Aeq}, and the differences between the frequencies of L_{Aeq} for occasions with and without LLWM increase, especially between 25.5 dBA and 33.5 dBA.

Criteria for Δu	$= 0.2\ m\ s^{-1}$		$= 0.5\ m\ s^{-1}$		$= 0.2\ m\ s^{-1}$		$= 0.5\ m\ s^{-1}$	
Criteria for *RF*	$\geq$ 0.0 *rpm*		$\geq$ 0.0 *rpm*		$\geq$ 14.0 *rpm*		$\geq$ 14.0 *rpm*	
Type of LLWM	*f* [%]	Amount	f [%]	Amount	f [%]	Amount	f [%]	Amount
All types	11.1	3552	6.8	2156	8.5	1108	5.5	723
Type I_a	1.1	359	0.6	194	0.9	114	0.5	62
Type I_b	3.8	1210	2.1	666	2.4	312	1.8	233
Type II_a	1.4	433	0.3	90	2.1	271	0.5	64
Type II_b	1.1	336	0.4	132	1.4	178	0.7	88

Note. Shown is the frequency (f in %) and the amount of 10-min averages (amount). Abbreviations: LLWM, low-level wind maxima; RF, rotational frequency.

TABLE 1 Occurrences of LLWM for all types and separated into the four types, with two different criteria for the *RF* in combination with two criteria for the difference between maximum wind speed and the second largest wind speed, Δu

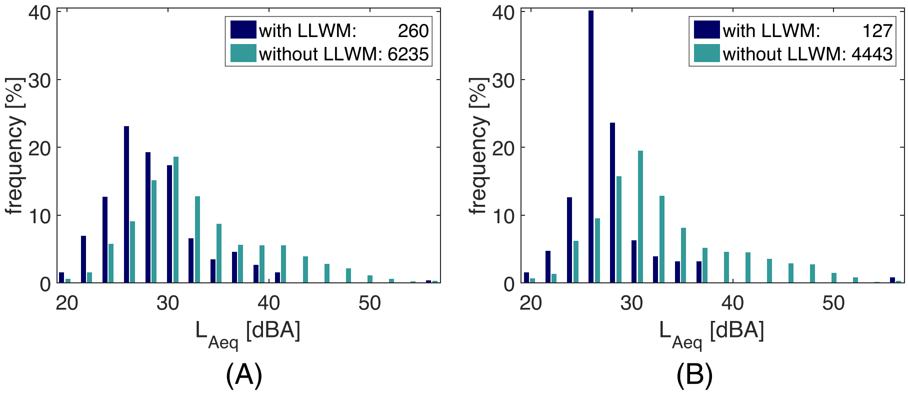

FIGURE 6 Frequency distributions of L_{Aeq} for occasions with and without LLWM for downwind conditions. The boundary conditions are *RF* $\geq$ 14.0 rpm and (A) $\Delta u = 0.2\ m\ s^{-1}$ and (B) $\Delta u = 0.5\ m\ s^{-1}$. The numbers in the legend refer to the amount of data [Colour figure can be viewed at wileyonlinelibrary.com]

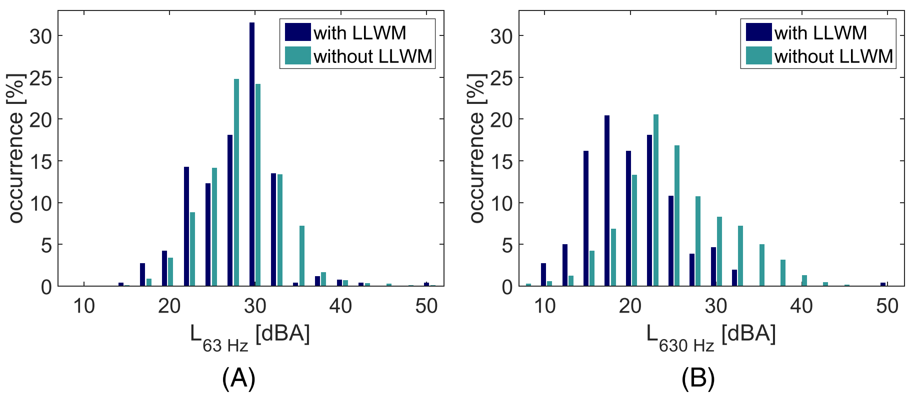

FIGURE 7 Occurrences of sound levels of (A) the 63-Hz 1/3-octave band, L_{63Hz}, and (B) the 630-Hz 1/3-octave band, L_{630Hz}, for occasions with and without low-level wind maxima (LLWM) for downwind conditions. The boundary conditions are *RF* $\geq$ 14.0 rpm and $\Delta u = 0.2\ m\ s^{-1}$ [Colour figure can be viewed at wileyonlinelibrary.com]

In a spectral analysis of the 1/3-octave sound levels between 80 and 2,000 Hz, a dependency of the frequency was seen, and two representative examples are shown in Figure 7, with 63 Hz in Figure 7A and 630 Hz in Figure 7B. Unlike the distributions shown in Figure 6, L_{63Hz} is distributed rather normally for occasions with and without LLWM (Figure 7A) and the differences between the distributions are small. In Figure 7B, both distributions are skewed towards higher L_{630Hz}, and the difference between the distributions with and without LLWM are larger than for the 63-Hz band. The shift towards lower sound levels for occasions with LLWM can be seen for frequency bands between 80 and 2,000 Hz. However, the shape of the distributions (for occasions with and without LLWM) changes with increasing frequency by an increasing skewness. Above 2, 000 Hz no obvious differences between the distributions for occasions with and without LLWM are observed, which is probably indicating low signal-to-noise ratios at these frequencies—lower signal strength due to atmospheric absorption can be suspected to dominate at these higher frequencies.

For LLWM with Δu = 0.2 m s^{-1}, the median of L_{Aeq} is 3.7 dBA lower compared with cases without LLWM (Table 2). For stronger LLWM (Δu = 0.5 m s^{-1}), the median of L_{Aeq} is 4.8 dBA lower compared with occasions without LLWM. This means that LLWM below hub height reduces the sound level downwind of a WT.

The highest L_{Aeq} in Figure 6, L_{Aeq} of ca. 50 dBA or greater, might occur due to ambient sound sources rather than due to WT sound. However, even if those L_{Aeq} are neglected, WT sound in the downwind direction is still lower if LLWM occur. Hence, the conclusion that LLWM below hub height reduce WT sound at the surface is still valid. The shown effect of LLWM on L_{Aeq} might even be underestimated since LLWM at altitudes below 60 m are not identified as LLWM with the current method. Therefore, they are instead included in the without LLWM category, thereby potentially reducing L_{Aeq} of this category. Another reason for a possible underestimation of the effect of LLWM on L_{Aeq} is temperature inversions. As discussed earlier, temperature inversions are also a feature of the SBL. The increase of temperature with height lead to downward refraction

TABLE 2 Medians of L_{Aeq} [dBA] for occasions with and without LLWM for two criteria of Δu and $RF \geq 14.0$ *rpm*

Criteria for Δu	$= 0.2$ m s^{-1}	$= 0.5$ m s^{-1}
With LLWM [dBA]	27.8	26.5
Without LLWM [dBA]	31.5	31.3

Abbreviations: LLWM, low-level wind maxima; RF, rotational frequency.

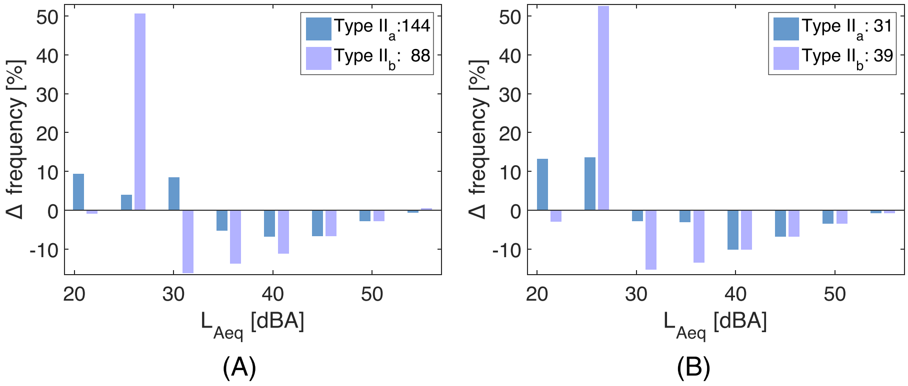

FIGURE 8 Differences between the frequency (%) of L_{Aeq} for occasions without low-level wind maxima (LLWM) and with LLWM (Type II$_a$ or Type II$_b$) for downwind conditions, $RF \geq 14.0$ rpm and (A) $\Delta u = 0.2$ m s^{-1} or (B) $\Delta u = 0.5$ m s^{-1}. The numbers in the legend refer to the amount of data [Colour figure can be viewed at wileyonlinelibrary.com]

(in a nonmoving atmosphere) and therefore to an increase in L_{Aeq} close to the surface. Since this effect counteracts the reducing effect of LLWM, the impact of LLWM might even be larger than the results shown in Figure 6 suggest.

The results presented here contrast strongly with the results of previous studies, which investigated the impact of LLWM on WT sound propagation.[11-14] Contrary to the findings described here, they found higher sound levels downwind of a WT due to enhanced downward fraction and trapping of the sound below the LLWM. The fundamental difference between these studies and the present is the location of the sound source relative to the LLWM. Here, the main sound source is located above (Type I$_a$ or Type I$_b$), or partly above (Type II$_a$ or Type II$_b$) the LLWM. Therefore, the sound is (partly) trapped above the LLWM. Hence, the concept is the same but the results are opposed, meaning that the higher the WTs, the less likely that residents will be disturbed by WT sound at this site.

4.3 | Impact of LLWM types

The differences between the frequency (%) of L_{Aeq} for occasions without LLWM and with LLWM (Type II$_a$ or Type II$_b$) for downwind conditions and $RF \geq 14.0$ rpm are shown in Figure 8. In Figure 8A, occasions for $\Delta u = 0.2$ m s^{-1} are presented, while in Figure 8B, the criterion is $\Delta u = 0.5$ m s^{-1}. Due to the lack of occurrence of Type I$_a$ and Type I$_b$ meeting the criteria $RF \geq 14.0$ rpm and $\Delta u = 0.2$ m s^{-1}, they are not part of this analysis.

Type II$_a$ mainly increases the frequencies of the lowest three sound-level interval bins (Figure 8A) and the lowest two sound-level interval bins (Figure 8B), respectively. Type II$_b$ increases the frequencies of $L_{Aeq} \approx 27$ dBA for both $\Delta u = 0.2$ m s^{-1} and $\Delta u = 0.5$ m s^{-1}. Partly, Type II$_a$ has a larger effect on L_{Aeq} than Type II$_b$, resulting in a relatively high occurrence of the lowest L_{Aeq}. Such low L_{Aeq} seldom occur for Type II$_b$, if at all. However, Type II$_b$ more often leads ($\approx 70\%$) to $L_{Aeq} < 28$ dBA than Type II$_a$ ($\approx 45\%$).

The overall effect of Type II$_a$ in relation to occasions without LLWM is a decrease in the median of L_{Aeq} by 2.0 dBA and 3.4 dBA for $\Delta u = 0.2$ m s^{-1} and $\Delta u = 0.5$ m s^{-1}, respectively. For Type II$_b$, the median of L_{Aeq} is decreased by 5.0 dBA and 4.4 dBA for $\Delta u = 0.2$ m s^{-1} and $\Delta u = 0.5$ m s^{-1}, respectively. The larger impact of Type II$_b$ can be explained by a stronger upward refraction due to a larger difference between $u_{82.5}$ and u_{105} compared with that of Type II$_a$. The larger difference exists because u_{105} is the lowest wind speed for II$_b$ but the second largest for II$_a$. That II$_b$ is more pronounced than II$_a$ can also be seen when comparing the ratio of occurrences for $\Delta u = 0.2$ m s^{-1} and $\Delta u = 0.5$ m s^{-1} (see Table 1). About 36% of Type II$_b$ with $\Delta u = 0.2$ m s^{-1} also meet $\Delta u = 0.5$ m s^{-1}, while it is about 21% for II$_a$.

5 | CONCLUSIONS

LLWM below hub height were investigated downwind of a wind farm in northern Sweden regarding their impact on L_{Aeq} close to the surface. Furthermore, the occurrence of LLWM and LLWM types of two levels of strength (i.e., $\Delta u = 0.2$ m s^{-1} and $\Delta u = 0.5$ m s^{-1}) were analysed. The main conclusions are as follows:

- LLWM can lower L_{Aeq} close to the surface in the downwind direction of a windfarm; the median of L_{Aeq} is lowered by up to 4.8 dBA compared with occasions without LLWM and depends on Δu.
- The stronger the LLWM (i.e., higher Δu), the larger its impact on L_{Aeq}.
- The effect of different LLWM types differs; the overall effect is larger if the wind speed above the maximum is lower than the one below the maximum (Type II$_b$) than for the opposite situation (Type II$_a$).

- The occurrence of LLWM types depends on the wind direction; LLWM were most common for wind directions around 200°, probably due to the topographical effect of two hills located in that direction.
- LLWM especially affect the sound level of the frequency bands between 80 and 2,000 Hz.

It is not clear if the observed LLWM occur at all the WTs at the investigated wind farm at approximately the same altitude. The LLWM are detected at the meteorological tower and due to the heterogeneity of the terrain, and they can occur at other altitudes at some of the WTs. If a LLWM is located above the hub of a WT, the effect will instead be reversed and lead to strong downward refraction and a higher L_{Aeq}.[12-14] Because of this amplifying effect, which is contrary to the attenuating effect shown here, the location of the LLWM relative to the main sound source is crucial for the resulting L_{Aeq} close to the surface downwind of a WT.

Potential LLWM between 4.6 m and 60 m are not detected with the current method and their effect might therefore lower L_{Aeq} for cases classified as without LLWM. In case of multiple LLWM, with one LLWM at 60 m or 82.5 m and another, potentially stronger one above 105 m, the combined effect would lead to an increase in L_{Aeq}. Since these cases would be classified as LLWM here, they counteract the effect of a single LLWM below hub height and increase L_{Aeq}. The present analysis is thus probably an underestimation of the damping by LLWM in cold climates.

Due to the heterogeneity of the measuring site, the conclusions concerning the occurrence of LLWM and the different types are presumably limited to this measuring site. Likewise, the dependence of the LLWM types on wind direction might well be different at other sites. Further studies at different sites could prove the generality of the conclusions regarding the impact of LLWM below hub height on L_{Aeq}.

Future studies including modelling of atmospheric conditions in order to identify LLWM in altitudes not covered by measurements are expected to substantially add to the knowledge on the impact of LLWM on WT sound propagation. Furthermore, the results presented here could be compared with future studies that focus on modelling of sound propagation for the different types of LLWM or occasions with LLWM in general. Moreover, detailed information on the location of the main sound source area would be beneficial for investigating small changes in LLWM height and the associated effects.

However, the damping effect of LLWM can be used, especially in the light of developing WTs with hub heights well above the altitude in which LLWM occur. As shown, LLWM can be a common feature below hub heights of about 100 m depending on the meteorological conditions and the terrain. Further measurements, which preferably consist of meteorological measurements with a high vertical resolution between the surface and several tens of meters above the hub, would be beneficial.

ACKNOWLEDGEMENTS

This study was financially supported by the Swedish Energy Agency (projects 40969-1 and 44948-1). The authors are also grateful to Vasa Vind, especially to Per Olof Renling for sharing operational and meteorological data. We would like to thank Dr Conny Larsson, who was the initial leader of the project.

FUNDING INFORMATION

This study was financially supported by the Swedish Energy Agency (projects 40969-1 and 44948-1).

CONFLICTS OF INTEREST

The authors declare no potential conflict of interests.

ORCID

Kristina Conrady https://orcid.org/0000-0003-1627-9096

REFERENCES

1. Johansson M, Laike T. Intention to respond to local wind turbines: the role of attitudes and visual perception. *Wind Energy*. 2007;10(5):435-451.
2. Michaud D, Feder K, Keith S, et al. Exposure to wind turbine noise: perceptual responses and reported health effects. *J Acoust Soc Am*. 2016;139(3):1443-1454.
3. Pedersen E, van den Berg F, Bakker R, Bouma J. Response to noise from modern wind farms in the Netherlands. *J Acoust Soc Am*. 2009;126(2):634-643.
4. Larsson C, Israelsson S. Effects of meteorological conditions and source height on sound propagation near the ground. *Appl Acoust*. 1991;33(2):109-121.
5. Salomons EM. *Computational atmospheric acoustics*. Dordrecht: Springer Netherlands; 2001. 335 pp.
6. Lamancusa JS. *Noise control–outdoor sound propagation*. Pennsylvania: Penn State University; 2008. 19 pp.
7. Andreas EL, Claffey KJ, Makshtas AP. Low-level atmospheric jets and inversions over the western Weddell Sea. *Bound Layer Meteorol*. 2000;97(3):459-486.
8. Tuononen M, Sinclair VA, Vihma T. A climatology of low-level jets in the mid-latitudes and polar regions of the Northern Hemisphere. *Atmos Sci Lett*. 2015;16(4):492-499.
9. Renfrew IA, Anderson PS. Profiles of katabatic flows in summer and winter over Coats Land, Antarctica. *Quart J R Meteorol Soc*. 2006;132(616):779-802.
10. Boué M. Long-range sound propagation over the sea with application to wind turbine noise. Final report for the Swedish Energy Agency project 21597-3(TRANS), Swedish Energy Agency; 2007. 68.

11. Makarewicz R. Downward refraction due to low level jet. *Act Acust United Acust*. 2016;102(4):640-644.
12. Johansson L. Sound propagation around off-shore wind turbines—long-range parabolic equation calculations for Baltic Sea conditions. *Licentiate Thesis*: KTH, Stockholm; 2003.
13. Törnblom K. Thermally driven wind modification in coastal areas and its influence on sound propagation with application to wind power. *Licentiate thesis*: Department of Earth Sciences, Uppsala University; 2006.
14. Bolin K, Boué M, Karasalo I. Long range sound propagation over a sea surface. *J Acoust Soc Am*. 2009;126(5):2191-7.
15. Barlas E, Zhu WJ, Shen WZ, Dag KO, Moriarty P. Consistent modelling of wind turbine noise propagation from source to receiver. *J Acoust Soc Am*. 2017;142(5):3297-3310.
16. Cotté B. Extended source models for wind turbine noise propagation. *J Acoust Soc Am*. 2019;145(3):1363-1371.
17. Makarewicz R, Gołebiewski R. The influence of a low level jet on the thumps generated by a wind turbine. *Renew Sustain Energy Rev*. 2019;104:337-342.
18. Oerlemans S, Sijtsma P, López BMéndez. Location and quantification of noise sources on a wind turbine. *J Sound Vibr*. 2007;299(4):869-883.
19. Conrady K, Sjöblom A, Larsson C. Impact of snow on sound propagating from wind turbines. *Wind Energy*. 2018;21(12):1282-1295.
20. Conrady K, Bolin K, Sjöblom A, Rutgersson A. Selection criteria for filtering wind turbine sound measurements. in preparation; 2019.

How to cite this article: Conrady K, Bolin K, Sjöblom A, Rutgersson A. Impact of low-level wind maxima below hub height on wind turbine sound propagation. *Wind Energy*. 2020;23:1767–1775. https://doi.org/10.1002/we.2517