Impact of snow on sound propagating from wind turbines

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Abstract
The impact of snow on sound propagating from a wind farm in northern Sweden has been investigated. Simultaneous acoustic and meteorological measurements, combined with daily snow observations, have been analysed for the snow season in 2013 to 2014. Such measurements are crucial since significant knowledge gaps exist, especially for conditions in cold climates, in the implementation of atmospheric boundary layer complexity in sound propagation models. The effect of snow on sound propagation is shown to be dependent on the snow quality. Moreover, snow on trees (upplega) also has an influence on sound propagation. Compared with conditions without snow on trees, the average sound level is approximately 2 dBA lower. The effect is more distinct for higher frequencies compared with lower frequencies.

KEYWORDS
atmospheric acoustics, refraction, snow, wind turbine sound

1 INTRODUCTION

Vast areas at high latitudes are covered by snow for several months per year. Snow covers not only the ground but also vegetation and constructions, a feature known as upplega. Snow changes the surface properties in many respects, e.g., by increasing the albedo and, therefore, playing an important role in the climate system of the Earth. In this regard, snow is a well-studied substance. However, the acoustic impact of snow has not nearly been investigated as extensively as its impact on climate, especially in the context of sound propagating from wind turbines.

The number of wind turbines in Sweden has been increasing during the last decade to more than 3000 in 2015.1 Starting from scarcely populated coastal sites, wind farms were built offshore but also spread inland. However, if wind farms are built in the vicinity of settlements, the wind companies may meet opposition. Even though the population density of these regions is often low, the quietness of the inland regions may be of high value to the local population and what attracts tourists. Furthermore, more than two-thirds of the Swedish land area is covered by forests.2 These densely forested regions require wind turbines with hub heights great enough to extend above the layer dominated by the influence of the trees on the air flow. In northern Sweden and other northern regions, constructing and operating wind farms is further complicated by the challenges of cold climates, for instance low temperatures and icing.

The atmospheric stratification in the boundary layer during winter is frequently stable with potential temperature increasing with height. Features of the stable boundary layer (SBL), as well as snow, are not yet or not sufficiently taken into account when planning wind farms, and the currently used models to predict sound propagation do not include SBL or snow (eg, Plovsing3). Van den Berg4 studied the effects of nocturnal wind profiles on sound propagating from wind turbines and concluded that the logarithmic wind profile is not sufficient to predict sound propagating from these wind turbines, and that it will lead to an underestimation of sound levels. The possibility that people who live in the vicinity of these wind farms complain about noise pollution generated by the wind turbines is then greater.5

The effect of snow on sound propagation has often been oversimplified in previous studies.6,7 Snow is usually described as one “substance” without taking into account the different types of snow. However, the properties of snow can alter the acoustic effect of the ground, which was previously concluded by Nicolas et al8 and Öhlund and Larsson.7 The latter found lower relative sound pressure levels (SPLs) when a snow cover was present when they investigated sound propagating from wind turbines.

The objective here is to investigate the impact of the snow on sound propagating from wind turbines in a stably stratified atmosphere, focusing both on snow on the ground and on trees. Section 2 describes the theoretical background for sound propagation outdoors, and in Section 3 the
measuring site and the measurements are presented. In Section 4, the meteorological and snow conditions are described. Section 5 and 6 present the results and are followed by the discussion and conclusions in Section 7.

2 | THEORETICAL BACKGROUND

Sound waves cause pressure deviations from the ambient atmospheric pressure. These deviations are called "sound pressure." The commonly used parameter in order to analyse sound sources or to set thresholds for sound emissions is the SPL. It is the effective sound pressure of a sound relative to a reference value and defined as

\[ L_p = 10 \log \frac{\text{prms}}{P_0} \text{ (dB)} = 20 \log \frac{\text{prms}}{P_0}, \]

where \( \text{prms} \) is the root mean square value of the signal. The reference pressure, \( P_0 \), is the threshold of audibility and equals \( 2 \times 10^{-5} \text{N m}^{-2} \) (20 \( \mu \text{Pa} \)) at 1000 Hz. To take the frequency dependence of human hearing into account, the SPL is A-weighted. This band pass filter simulates the frequency curve, which is linked to the equal loudness of human hearing. Even though it is a representation of human hearing at a loudness of 40 phon (ie, 40 dB at 1000 Hz), it is in practice used for all loudness levels. The unit of the A-weighted SPL is then dBA.

The relative SPL, \( \Delta L \), is determined by subtracting the SPL calculated for free field conditions from the measured SPL at the receiver, \( L_{\text{ref A}} \) (dB):

\[ \Delta L = L_{\text{ref A}} - 10 \log \sum_i 10^{\log_{10} 10^{L_{\text{WA}}}} R_i, \]

where \( L_{\text{WA}} \) is the emitted sound power level from each wind turbine \( i \) (dB; see Section 3.2), \( R_i \) is the distance between the receiver and each wind turbine \( i \), and \( \alpha \) is the atmospheric absorption coefficient (dBm\(^{-1}\)). In the free field value, atmospheric absorption and spherical spreading are taken into account since wind turbines are approximated as point sources. That means positive \( \Delta L \) indicates amplification, while negative \( \Delta L \) indicates damping (eg, other studies\(^5,7\)). In a nonmoving atmosphere, the speed of a sound wave is dependent on the temperature and humidity of the air. In a moving atmosphere, the effect of wind speed and wind direction could be approximated by the effective sound speed, \( c_{\text{eff}} \), at the height \( z \) (m)\(^7,9\):

\[ c_{\text{eff}}(z) = \sqrt{R_t z (1 + 0.16q(z)) + u_{\text{comp}}(z)}, \]

where \( \gamma \) represents the ratio of the specific heat at a constant pressure and the specific heat at a constant volume,\(^10\) \( R_t = 287.066 \text{ J kg}^{-1} \text{ K}^{-1} \) is the universal gas constant for dry air, \( T \) is the temperature (K), and \( q \) is the specific humidity (kg kg\(^{-1}\)). The first term on the right hand side accounts for the sound speed in a nonmoving atmosphere. The second term, \( u_{\text{comp}}(z) \), which is the horizontal component of the wind speed in a specific sound propagation direction (ms\(^{-1}\)), is defined as

\[ u_{\text{comp}}(z) = -|U(z)| = \cos(\omega z) - \text{dir}, \]

where \( \omega \) is the wind direction (\(^\circ\)), \( U \) is the wind speed (ms\(^{-1}\)), and dir is the sound propagation direction (\(^\circ\)), ie, dir = 0\(^\circ\) indicates northward propagation, whereas dir = 90\(^\circ\) indicates eastward propagation.

Vertical gradients of temperature or wind speed result in upward or downward bending of the sound wave paths, which is called "refraction" (Figure 1, based on, eg, Lamancusa\(^11\)). A measure for the refraction of sound waves is the vertical gradient of \( c_{\text{eff}} \), \( \Delta c_{\text{eff}} \):

\[ \Delta c_{\text{eff}} = \frac{c_{\text{eff}}(z_2) - c_{\text{eff}}(z_1)}{z_2 - z_1}, \]

where \( z_1 \) and \( z_2 \) are two different heights.

The sound waves are bent to regions of lower sound speed while moving forward. Positive \( \Delta c_{\text{eff}} \), which leads to downward bending, occur because of an increase in \( u_{\text{comp}} \) (Figure 1A) with height and/or a positive temperature gradient (Figure 1B). Downward bending usually results in higher SPLs since the sound waves are reflected by the surfaces they reach. Whereas upward bending occurs because of negative \( \Delta c_{\text{eff}} \), which can be caused by a decrease in \( u_{\text{comp}} \) with height and/or a negative temperature gradient (Figure 1C). Upward bending can result in regions that are not directly reached by sound waves—ie, shadow zones. These zones are usually characterised by low SPLs, however, even they can be penetrated by sound waves due to other effects, eg, scattering caused by turbulence. Furthermore, humidity is involved but plays only a minor role compared with wind and temperature gradients.

Interaction between sound waves and the ground is more intensive during downward than upward bending. A positive temperature gradient, which is typical in cold climates, enhances the interaction especially downwind of the source (see Figure 1). As with every interface between two different media, the waves are altered in several ways by interacting with the "new" medium. If a ground-reflected wave meets a direct wave—which, so far, did not interact with the ground—interference takes place, and results in the ground effect.\(^12\) Due to the different distances they travelled and the resulting delay, the phases of the reflected and the direct waves are different. Dependent on the phase difference, constructive or destructive interference may occur, which causes greater or lower SPLs, respectively.

Following Attenborough,\(^12\) the most important parameter characterising the ground from an acoustic point of view is its flow resistivity. High values mean that air cannot easily penetrate into or exit the ground, which is typically linked to a low porosity. The more porous the uppermost layer of the ground is, the more important its thickness becomes, as well as potential sublayers. High porosities lead to a decreased reflection at the surface, hence lower SPLs compared with surfaces of low porosity. However, the impact of porous surfaces on reflection is frequency dependent.
FIGURE 1  Refraction due to A, wind speed gradients (isothermal atmosphere) and in a nonmoving atmosphere due to B, a positive and C, a negative temperature gradient, where $z$ is height, $u$ is wind speed, and $T$ is temperature. Bold arrows show the path of direct sound waves, and dashed arrows reflected paths [Colour figure can be viewed at wileyonlinelibrary.com]

The longer the wave length, the less able the wave is to enter the ground through the pores, and the more likely reflection is at the surface. Bucur concludes that ground attenuation increases with increasing frequency.

It is mainly the acoustical ground characteristics of the area close to the sound source and the receiver that influence the sound propagation for downward refracting conditions. To which extent these two regions and the region between those are contributing to the total effect is dependent on the height of the source and the height of the receiver. Since the ground properties of one region are likely to be nonhomogeneous, the determination of the ground effect is complex, and an implementation into a model is not trivial. The fact that a certain ground may change its acoustical properties with time makes it even more complex. The flow resistivity may vary because of different kinds of precipitation and their effect on the ground, the growth of vegetation, freezing of the ground, and human construction activities. Snow in general has a low resistivity, however, it differs depending on the snow’s properties. Previous studies are mainly focused on the silencing effect of snow (eg, Nicolas et al) and do not differentiate between different types of snow (eg, other studies).

Large positive vertical gradients of temperature or wind speed can cause an extreme downward bending of the sound waves, preventing them reaching other heights than those close to the ground. In other words, the large gradients limit the normally spherical spreading from a point source by creating an upper boundary, which leads to a shift to cylindrical spreading. If the source is approximated as a point source, the decrease of sound pressure by doubling the distance between source and receiver is usually 6 dB. However, due to the shift to cylindrical spreading, it is 3 dB instead, that, in turn, leads to higher SPLs. Additionally, it leads to a higher relevance of the ground effect due to an increased possibility of multiple sound reflections. This feature is called “stratified spreading”.

Turbulence has an impact on sound propagation. Turbulent eddies lead to a reduction in coherence between the propagation paths of the waves. That process leads to fluctuations in both the amplitudes and phases of the waves, which in turn leads to local fluctuations in SPLs. In cold climates, the turbulence level is lower than in other climates and thus plays a minor role in sound propagation. However, it cannot be completely neglected because intermittent turbulence is a typical process in the SBL.

3  MEASUREMENTS AND DATA PROCESSING

3.1  Measuring site and instrumentation

The measuring site is located close to a wind farm slightly to the south of the Arctic Circle in northern Sweden. A snow cover is usually present from the end of October to mid-May. The wind farm is sited in an undulating landscape surrounded by forests and swamps. Currently, it consists of 12 Enercon E822MW wind turbines, but those are planned to be the initial point for a comprehensive project including a large number of wind turbines. One to 2 km northeast of the wind turbines, acoustic measurements are conducted with a Norsonic Nor140 sound level meter and a Nor1214 outdoor 1/2″ microphone equipped with a rain hood and a protecting mesh. The instruments are situated on a slope in a forest at an altitude approximately 40 m lower than the wind turbines. The microphone is not shielded from the wind turbines by topography but might be in a shadow zone depending on the refraction conditions. An 18-m mast is providing temperature, wind speed, and wind direction measurements at 0.5, 1.5, 5, and 18 m, as well as atmospheric pressure and relative humidity at 1.5 m. The mast is located in a valley 60 m lower than the wind turbines on the north eastern edge of the forest and only the highest level of the mast is above the tree crowns. Both meteorological and acoustic measurements are averaged over the same 10-minute interval. Measurements of snow depth and observations of the snow quality are taken close to the 18-m mast once a day by local residents. Additionally, the information if snow on vegetation, especially on trees, is present or not is recorded. Moreover,
Overview of the experimental set-up: A, wind farm (black dot), meteorological tower (red dot); the numbers indicate the height above sea level, roads (bold lines), railway (dashed line), and the grey rectangle the zoomed in area shown in B. B, Close-up of the measuring site, with 12 wind turbines (black dots), acoustic station (blue +), and an 18-m mast (red cross), roads (bold lines), small streets (dotted lines), railway (dashed line). Panel C shows a schematic cross section of the set-up [Colour figure can be viewed at wileyonlinelibrary.com]

![Figure 2](image-url)

**TABLE 1** Instrumentation at the 18-m mast and the tower, where T, RH, p, u, and wd stand for temperature, relative humidity, atmospheric pressure, wind speed, and wind direction, respectively

<table>
<thead>
<tr>
<th>Mast/Tower</th>
<th>Level, m</th>
<th>Parameter</th>
<th>Sensor</th>
</tr>
</thead>
<tbody>
<tr>
<td>18-m mast</td>
<td>0.5</td>
<td>T</td>
<td>Rotronic HC2S3</td>
</tr>
<tr>
<td></td>
<td>1.5</td>
<td>T, RH, p, u, wd</td>
<td>Rotronic HC2S3, Sensortec barometer</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>T, u, wd</td>
<td>Rotronic HC2S3</td>
</tr>
<tr>
<td></td>
<td>18</td>
<td>T, u, wd</td>
<td>Rotronic HC2S3</td>
</tr>
<tr>
<td>Tower</td>
<td>4</td>
<td>T</td>
<td>Rotronic HC2S3</td>
</tr>
<tr>
<td></td>
<td>98</td>
<td>T, RH, p</td>
<td>Rotronic HC2S3, Vaisala PTB110</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>u</td>
<td>Vaisala WAA252</td>
</tr>
<tr>
<td></td>
<td>118</td>
<td>wd</td>
<td>NRG Ice Free II</td>
</tr>
<tr>
<td></td>
<td>120</td>
<td>u</td>
<td>Vaisala WAA252, Thies FC</td>
</tr>
<tr>
<td></td>
<td>136</td>
<td>T</td>
<td>Rotronic HC2S3</td>
</tr>
</tbody>
</table>

Meteorological data from an additional tower is used. This tower is located 10 km southeast from the microphone, on a hill at approximately the same height as the wind turbine hill (see Figure 2 and Table 1).

A small settlement and a road with little traffic is located 1 km northeast of the acoustic station. The snow season between 05.11.2013 and 30.04.2014 is investigated.
3.2 Processing of acoustic data

Although the microphone is located some hundred meters away from the closest building, the roads in the area are not frequently used and a background level under 20 dBA is not uncommon, it is likely that the sound recorded is not only emitted by the wind turbines. Wind-induced sound from vegetation and sound from animals are two sources of background sound, but other sound sources, eg, air planes and snowmobiles, can possibly interfere with the measurements. To minimize the possibility of taking background sound erroneously for wind turbine sound, a selection method including three criteria to select the data, following Öhlund and Larsson, was used.

The aim is to identify all 10-minute intervals during which the wind turbines are the dominant sound source. The first criterion rejects measurements with too high variations since that is an indication of background sound. Thus, a 10-minute interval is rejected if

$$L_{5} - L_{95} > 4 \text{ dBA},$$

where $L_{5}$ and $L_{95}$ are fifth and 95th percentiles, respectively. The second criterion takes into account that high frequencies, if emitted by the wind turbines, are most likely absorbed on the way between the wind turbine and the microphone. Hence, the measurement is rejected if

$$10 \log_{10} \sum_{i=800 \text{ Hz}}^{20 \text{ kHz}} 10^{\frac{L_{Ai}}{10}} \geq 800 \text{ Hz} \quad 10^{L_{pAi}} \geq 1.5 \text{ dBA} \quad \land \quad L_{Atot} > 25 \text{ dBA},$$

where $L_{pAi}$ are the measured SPLs at the receiver for each 1/3 octave band for frequencies between 800 Hz and 20 kHz, and $L_{Atot}$ is the total A-weighted SPL. The third criterion ensures that the wind turbines produce enough sound, which means that the total SPL must be 30 dBA or above at the point of immission, based on calculations of free-field spreading from every turbine.

Emitted sound power levels for each wind turbine were determined for every 10-min interval based on the specifications of the manufacturer and operational data (see Equation 2). For that, the rotational frequency of the turbines was converted to electrical power, which in turn, was related to an emitted sound power level. The wind turbines are treated as individual point sources with the nacelle as the centre. The individual distances between each wind turbine and the receiver, the different hub heights, and the meteorological measurements, are used to calculate the SPL for free field conditions.

4 OVERVIEW OF METEOROLOGICAL AND SNOW CONDITIONS

The area around the wind farm is heterogeneous with hills partly covered by forests and swamps, traversed by lakes and rivers. The tower is situated on a hill up to 200 m above its surroundings 10 km southeast of the wind farm (Table 1 and Figure 2). Flow over complex terrain and hills has been investigated in many studies. The height of a hill tends to increase the mean wind speed because of the speed-up effect on the incoming wind field. However, complex terrain may also induce blocking effects, high wind shear, flow separation, and an increased level of turbulence. Stratification also influences flow over hills. During unstable and near neutral stratification, the flow goes over the hill and the wind speed increases, but during stable stratification, the air tends to flow around the hill giving a much lower wind speed at the summit.

Figure 3 shows the frequency distribution of wind speed at the tower for the measuring period. The distribution shows a much higher frequency for high wind speeds ($> 7 \text{ m s}^{-1}$) compared with measurements taken in flat terrain. This is an indication of the speed-up effect at the top of the hill. Compared with wind conditions in flat terrain, the frequency distribution shows a plateau between 8 and 13 m s$^{-1}$ rather than a distinct maximum (compare, eg, Figure 4C). A specific distribution of large-scale forcing during the measuring period might be an additional reason for the high frequency of high wind speeds.

**FIGURE 3** Distribution of wind speed at 120 m (tower) between 05.11.2013 and 30.04.2014 [Colour figure can be viewed at wileyonlinelibrary.com]
The data presented in the following paragraphs originate from the 18-m mast close to the acoustic station, if not further specified. The temperature varied between $-26.1^\circ C$ and $13.7^\circ C$ with an average temperature of $-3.7^\circ C$ and 74% of the data record temperatures below $0^\circ C$ (Figure 4A). The coldest days were between 10.01.2014 and 02.02.2014, when the temperature did not exceed $-9^\circ C$, which resulted in an average temperature of $-15.2^\circ C$. The temperatures at the tower (4 m) were usually lower than at the 18-m mast: 66% of the time. Around two-thirds of the measured relative humidity values are above 80% (Figure 4B), the relative humidity being noticeably lower during the end of the period.

The wind conditions at the 18-m mast are, at least partly, influenced by the forest and a northwest facing slope west of the mast. Even though the tree crowns are below the 18-m level, the average wind speed was as low as 2.1 ms$^{-1}$, and the 10-minute averages did not exceed 5.5 ms$^{-1}$ (Figure 4C). The difference in wind speed between the 18-m level at the 18-m mast and the 120-m level at the tower was usually around 2 to 10 ms$^{-1}$, but reached values up to 16.5 ms$^{-1}$. Wind speed measurements were conducted simultaneously with two different instruments, a Vaisala WAA252 (heated) and a Thies FC (not heated), at several heights up the tower (see Table 1). The two types of wind sensors showed high correlations with correlation coefficients of 0.99 for all towers and levels. The heated Vaisala WAA252 was mainly used for the wind speed; however, the Thies FC was used to fill data gaps. The main wind directions (c. 40% of the time) were between 180$^\circ$ and 225$^\circ$ (Figure 4D) that is the same if only wind speeds
above 2 ms\(^{-1}\) are taken into account. The prevailing wind direction at the tower (118 m) was west-southwest, which corresponds to wind coming from the wind turbines towards the sound measurement location.

An overview of the snow depth and upplega is given in Figure 5. Between 05.11.2013 and 30.04.2014 the lowest snow depth was 20 cm. In May, the snow cover became more inhomogeneous because of melting. Periods with upplega lasted usually from a few days to a couple of weeks.

5 | IMPACT OF SNOW QUALITY

Snow quality was classified as dry, damp, wet, or frozen, ie, the system used by Lundberg and Halldin, who distinguished only between dry and wet snow, was here complemented with damp and frozen snow. The classification is based on the hypothesis that different snow qualities have different surface characteristics and therefore diverse acoustic effects. The data set used for the classification consists of descriptive, qualitative observations rather than measurements. The observer noted the appearance and the texture of the snow. These observations were divided into four categories; however, some observations could not be assigned to any of the categories. In Table 2, the number of occasions for each snow quality is given along with mean values of several meteorological parameters for the respective conditions, indicated by an overline. Dry snow with a mean temperature of \(-8.95\degree C\) at 0.5 m, \(T_1\), is more than 6\degree C lower compared with the other snow qualities. \(T_1\) is only positive for wet snow. The averaged specific humidity, \(\bar{q}\), is greatest during wet and damp snow, while the averaged relative humidity, \(\bar{RH}\), reaches a maximum for damp and dry snow. The bulk Richardson number is used as a measure of atmospheric stability and calculated as follows:

\[
R_iB = \frac{g}{\theta_{1.5}} \left( \frac{\theta_{98} - \theta_{18}}{z_{98} - z_{18}} \right) \left( \frac{u_{100} - u_{18}}{z_{98} - z_{18}} \right)^{-2}, \tag{7}
\]

where \(g = 9.81\text{ms}^{-2}\) is the gravitational acceleration, \(\theta\) is the potential temperature (K), \(z\) is the measuring height (m), and \(u\) is the wind speed (ms\(^{-1}\)). The indices indicate the measuring heights. Note that 1.5 and 18 m refer to the 18-m mast, while 98 and 100 m refer to the tower. The atmosphere is on average stably stratified (ie, \(R_iB > 0\)) if dry snow is present, neutral (\(R_iB = 0\)) for wet snow, and unstable (\(R_iB < 0\)) for damp and frozen snow conditions. Results from wet snow observed on 42 occasions should, however, be treated with caution due to the small sample size. A maximum of 144 occurrences per day is possible, and all occasions with wet snow could hence be detected during quite similar atmospheric conditions within a period of a few hours.

### Table 2: Different snow qualities, number of days and occasions, mean values of temperature, \(\bar{T}_1\), specific humidity \(\bar{q}\), relative humidity \(\bar{RH}\), and bulk Richardson number, \(\bar{R}_iB\)

<table>
<thead>
<tr>
<th>Snow quality</th>
<th>Number of days</th>
<th>Number of occasions</th>
<th>(\bar{T}_1) [(^\circ)C]</th>
<th>(\bar{q}) [g kg(^{-1})]</th>
<th>(\bar{RH}) [%]</th>
<th>(\bar{R}_iB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry</td>
<td>81.5</td>
<td>2554</td>
<td>-8.95</td>
<td>2.01</td>
<td>89</td>
<td>0.16</td>
</tr>
<tr>
<td>Damp</td>
<td>26.5</td>
<td>629</td>
<td>-1.31</td>
<td>3.26</td>
<td>90</td>
<td>-0.10</td>
</tr>
<tr>
<td>Wet</td>
<td>2</td>
<td>42</td>
<td>0.89</td>
<td>3.47</td>
<td>83</td>
<td>-0.01</td>
</tr>
<tr>
<td>Frozen</td>
<td>22</td>
<td>422</td>
<td>-2.32</td>
<td>2.53</td>
<td>75</td>
<td>-0.06</td>
</tr>
</tbody>
</table>

*Note that the number of occasions show how many data points exist for each snow quality and when a relative sound pressure level value is available.*

FIGURE 6 Distribution of sound pressure level, \(\Delta L\), for occasions with dry (blue), damp (green), frozen (orange), and wet snow (purple) [Colour figure can be viewed at wileyonlinelibrary.com]
Frequency distributions of $\Delta L$ are broadly similar for damp and frozen snow (Figure 6) and are normally distributed. However, for damp snow, $\Delta L$ varied more with greater values than for frozen snow. Dry snow shows an even greater variation and is skewed towards negative values. Dry snow shows a local maximum around 2 dBA and a second around –11 dBA, which could indicate the existence of two major types of dry snow. This was explained by Albert,\textsuperscript{22} where two forms of dry snow were found to have different effective flow resistivities, $\sigma$. Dry snow with flat grains gave $\sigma = 55 \text{ kNsm}^{-1}$, in contrast to $\sigma = 11 \text{ kNsm}^{-1}$ for dry snow with spherical grains. A second explanation is that the lower local maximum coincides with atmospheric conditions that favour downward refraction. Most of the low $\Delta L$ coincide with a period during which wind speed and wind direction data from most of the instruments are lacking. Thus, it is not possible to calculate $\Delta c_{\text{eff}}$ and determine whether these low $\Delta L$ are caused by upward refraction. However, wind direction measurements at 5 m (18-m mast) show that most of the low $\Delta L$ occur during upwind conditions. Therefore, the effect of $\Delta c_{\text{eff}}$ was investigated further for the four snow qualities. Moreover, the effect of upplega was examined in order to see if the additional snow on the trees may enhance the differences between the snow qualities.

5.1 Effect of the effective sound speed gradient

To cover the whole layer between the source and the surface, the lowest data should ideally originate from the surface ($z = 0 \text{ m}$). However, no measurements were conducted at that level, and the instruments at the next higher level ($z = 0.5 \text{ m}$) were covered by snow most of the time. Therefore, $\Delta c_{\text{eff}}$ (Equation 5) was calculated between the 1.5-m (18-m mast) and around the 120-m level (tower). In this case, 120-m level means wind speed measurements at 120 m, wind direction at 118 m, relative humidity and air pressure at 98 m, and temperature at 98 m, using measurements at 136 m for height correction. The sound propagation direction, $\text{dir}$, employed for calculating $u_{\text{prop}}$ (Equation 4), is 37°. $\Delta c_{\text{eff}}$ affects $\Delta L$ for all snow qualities (Figure 7A). Since negative $\Delta c_{\text{eff}}$ occurred almost exclusively during dry-snow conditions, a comparison of the different snow qualities can only be made for the occasions with downward bending (ie $\Delta c_{\text{eff}} > 0$).

No, or light downward bending, in combination with damp snow gave the highest $\Delta L$, while it led to $\Delta L$ around 0 dBA when dry, frozen, and wet snow was present. For increasing downward bending, $\Delta L$ decreases for damp snow but increases for the other snow qualities. Between $\Delta c_{\text{eff}} = 0.05$ and 0.07 s$^{-1}$, the medians for dry, damp, and frozen snow are similar; however, the standard deviation for dry snow is higher than for damp and frozen snow. For strong downward bending, $\Delta L$ is decreasing for dry snow while slightly increasing for frozen snow. Note, however, that the bin including the lowest $\Delta c_{\text{eff}}$ values for frozen snow represents only seven data points. $\Delta c_{\text{eff}}$ clearly has an influence on $\Delta L$; however, it does not explain the difference between the different snow qualities.

$\Delta c_{\text{eff}}$ has an even larger influence when only occasions with upplega are taken into account (Figure 7B). Even though the sample size is relatively small, the differences between the medians for the corresponding $\Delta c_{\text{eff}}$ are clearly larger compared with those shown in Figure 7A. Therefore, there is an influence of upplega on sound propagation in addition to snow quality and $\Delta c_{\text{eff}}$, which is further investigated in the section below.

5.2 Effect of upplega

The four snow qualities are additionally split into occasions with and without upplega, and $\Delta L$ is analysed separately (Figure 8 and Table 3). For dry snow, the distribution of $\Delta L$ for upplega has a maximum around 0 dBA and a smaller cluster around –11 dBA. If upplega is not present, $\Delta L$ is usually around 2 dBA. Negative $\Delta L$ occurs 58% of the time for upplega, compared with only 16% for no upplega. If damp snow is observed, approximately 33% of the $\Delta L$ values are negative for upplega, while they are unusual (2%) without upplega. While on average upplega leads to lower $\Delta L$ if dry or damp snow is present, the opposite holds for frozen snow. Here, all $\Delta L$ values are positive for upplega, and around 90% are positive for no-upplega occasions. Furthermore, $\Delta L$ in Figure 8B shows more or less homogeneous distributions around the medians for all snow qualities except wet snow, whereas the distributions for upplega (Figure 8A) do not show such a consistency.

![FIGURE 7](https://wileyonlinelibrary.com) Relative sound pressure level, $\Delta L$, as a function of effective sound speed gradient, $\Delta c_{\text{eff}}$, calculated between 120 and 1.5 m for dry (blue, dashed), damp (green, dotted), frozen (orange, dashed-dotted), and wet snow (purple) for A, all data and B, occasions with upplega. Circles, bars, and numbers indicate medians, one standard deviation, and sample size of each bin, respectively [Colour figure can be viewed at wileyonlinelibrary.com]
### Table 3

<table>
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<th></th>
<th>Dry</th>
<th>Damp</th>
<th>Frozen</th>
<th>Wet</th>
<th>All</th>
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<td>2.0</td>
<td>3.6</td>
<td>...</td>
<td>−1.6</td>
</tr>
<tr>
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<td>3.9</td>
<td>2.4</td>
<td>0.8</td>
<td>2.7</td>
</tr>
<tr>
<td>All</td>
<td>−0.5</td>
<td>3.4</td>
<td>2.5</td>
<td>0.8</td>
<td>0.5</td>
</tr>
</tbody>
</table>

#### Figure 8

Distribution of relative sound pressure level, ΔL, for A. upplega and B. no upplega with dry, damp, frozen, and wet snow. The central line indicates the median, the edges of the box indicate the 25th and 75th percentile, respectively. Whiskers reach the most extreme points when excluding outliers (blue +), i.e., values more than 1.5 times the interquartile range away from the edges of the box [Colour figure can be viewed at wileyonlinelibrary.com]

#### 6 Impact of Upplega

The distinct differences between ΔL for occasions with and without upplega (Figure 8 and Table 3) suggests that upplega crucially alters the flow resistivity of the surface of the trees. Moreover, snow partly fills the space between the branches and neighbouring trees. Hence, there is extra material that potentially blocks and absorbs sound waves. Therefore, all data was separated into upplega (1990 occasions) and no-upplega (1869 occasions) independent of the snow quality. A frequency distribution (Figure 9) for upplega is bimodal and shows a peak located at approximately ΔL = −2 dBA and a weaker peak at around ΔL = −12 dBA, while the occasions without upplega show only one peak at around ΔL = 2.5 dBA. Since ΔL < −5 dBA occur mainly during downwind conditions, the lower peak might be caused by downward refraction. There are also distinct differences in the range. While maximum values of ΔL are almost similar for both cases, around 11 dBA, values below −5 dBA can only be found for occasions with upplega; values as low as −18 dBA were observed.

#### Figure 9

Distribution of relative sound pressure levels for occasions with upplega (purple) and no upplega (green) [Colour figure can be viewed at wileyonlinelibrary.com]
The dependence of $\Delta L$ on $\Delta c_{\text{eff}}$ for occasions with and without upplega is shown in Figure 10. If upplega is observed, the medians of $\Delta L$ are around 2 dBA lower than without upplega. In both cases, $\Delta L$ is lower for negative $\Delta c_{\text{eff}}$, i.e., upward bending, than for positive $\Delta c_{\text{eff}}$, i.e., downward bending. The shape of the curves is similar to that for dry snow presented in Figure 7A. Furthermore, slightly negative and positive $\Delta c_{\text{eff}}$ result in amplification, while more negative $\Delta c_{\text{eff}}$ cause a damping of the sound. Note, however, that the two bins for the most negative $\Delta c_{\text{eff}}$ values only contain six data points each. Nevertheless, a meteorological effect through a dependency on $\Delta c_{\text{eff}}$ on $\Delta L$ is clearly recognizable for conditions both with and without upplega. Furthermore, the effect of upplega is independent of the refraction.

The data shown in Figure 10 was split into six different 1/3-octave bands (Figure 11). The 63 and 125 Hz bands (Figure 11A and B) are similar regarding the dependency of $\Delta L$ on $\Delta c_{\text{eff}}$. Both have lower $\Delta L$ for negative $\Delta c_{\text{eff}}$ and higher $\Delta L$ for positive $\Delta c_{\text{eff}}$, as seen before in Figure 10. Differences between occasions with and without upplega are negligibly small, except for the 63 Hz band and negative $\Delta c_{\text{eff}}$, where $\Delta L$ is higher for upplega.
However, ΔL is almost exclusively negative for the 63 Hz band, while for the 125 Hz band, ΔL is slightly positive—around 5 dBA—for positive Δceff and negative for negative Δceff. For the 250 Hz band (Figure 11C), slightly positive ΔL and no clear differences between upplega and no upplega occurred for positive Δceff, whereas for negative Δceff, ΔL is decreasing with decreasing Δceff (except for the median of the lowest bin). The medians for upplega are lower and decrease with decreasing Δceff more than the medians for no upplega. Both the 500 and 1000 Hz band (Figure 11D,E) reveal smaller median ΔL for upplega than for no upplega. For negative Δceff, ΔL is lower for both frequency bands if upplega is present. ΔL does not show a strong dependency on Δceff for occasions without upplega and is in general higher for the 1000 Hz band than for the 500 Hz band. In contrast to the other frequency bands, the 2000 Hz band ΔL is relatively high and not clearly lower for negative Δceff than for positive Δceff (Figure 11F). The contribution of wind turbine sound within the 1000 and 2000 Hz bands is small and therefore the effect of Δceff minor. However, ΔL is greater for no upplega than for upplega here, too.

Even though the meteorological conditions which favour upplega are not entirely known, they might themselves influence sound propagation and hence lead to the effect attributed to upplega. Therefore, the dependency on ΔL of atmospheric stability, temperature at 0.5 m, and wind direction was analysed separately. The gradient of the potential temperature, \( \Delta \theta \Delta z^{-1} \), between 1.5 and 18 m was used as a measure for the stability since wind speed measurements could not be used. Figure 12 shows that the variation of ΔL is relatively high for \( \Delta \theta \Delta z^{-1} < 0.05^\circ C m^{-1} \) but decreases with increasing gradients. Occasions with upplega (Figure 12A) clearly differ from those without upplega (Figure 12B and 12C). For the latter, ΔL of about 10 dBA was observed during gradients between 0°C m⁻¹ and 0.01°C m⁻¹. ΔL decreases with increasing gradients and approaches a mean value of around 2 dBA. For \( \Delta \theta \Delta z^{-1} > 0.1^\circ C m^{-1} \), the gradient of potential temperature has no impact on ΔL during occasions without upplega. In particular, dry and damp snow exhibit this behaviour. When frozen snow is present, ΔL decreases linearly with increasing gradients. For occasions with upplega, this cannot be observed, but the variation in positive and negative direction of ΔL is decreasing with increasing gradients.

Additionally, the bulk Richardson number (\( R_{ib} \)) was investigated. However, since the 18-m mast is located close to a forest, the wind speeds at the lower three measuring heights are rather low. Therefore, \( R_{ib} \) was calculated using the highest level in the 18-m mast and the lowest wind sensor at 98 m at the tower (not shown, Equation 7). Accordingly, the results should be treated with caution, because the boundary layer height is likely to be below 98 m, and there is a distance of approximately 10 km between the two measuring locations. The results are similar to those for vertical gradient of potential temperature. ΔL is greater for negative \( R_{ib} \) (unstable) and decreases with increasing \( R_{ib} \) (increasing stability) for occasions without upplega.

![Figure 12](https://wileyonlinelibrary.com)  
**Figure 12** ΔL as a function of the gradient of potential temperature between 1.5 and 18 m: A, upplega; B, no upplega, and C, a zoomed-in section of B [Colour figure can be viewed at wileyonlinelibrary.com]
FIGURE 13  $\Delta L$ as a function of A, the temperature at 0.5 m and B, wind direction at 5 m for wind speeds higher than 0.2 ms$^{-1}$ (purple +) with upplega and (green triangle) without upplega [Colour figure can be viewed at wileyonlinelibrary.com]

Figure 13A shows that surface temperatures ($z = 0.5$ m) are usually lower when upplega are present. Again, $\Delta L$ is on average lower for upplega than no upplega, even if the same temperature ranges are compared. Hence, an effect of the temperature on relative SPLs might be possible, although the effect of upplega is independent of the surface temperature. The distribution of wind direction for occasions with and without upplega are fairly similar (Figure 13B), but the magnitude of $\Delta L$ is different. There is a dependency of $\Delta L$ on wind direction, with the greatest $\Delta L$ for southwesterly winds and the least for northerly and northeasterly winds. Note that the wind direction measurements shown in Figure 13B were made at the 18-m mast and are therefore affected by the forest. The reason for showing these measurements is that others were not available for a period during which $\Delta L$ was low, around $-15$ dBA. Even though these meteorological parameters have an influence on $\Delta L$, neither of them explain why lower $\Delta L$ occur when upplega is present.

7  DISCUSSION AND CONCLUSIONS

The impact of snow quality and upplega on sound propagating from a wind farm in northern Sweden was analysed during the snow season in 2013 to 2014. The aim was to investigate whether snow quality influences wind turbine sound and if upplega has an impact on the ambient SPL.

Sound propagation is complex, especially if the sound is propagating from an elevated source in undulating terrain during varying meteorological conditions. Due to the directivity of the source and the inhomogeneous character of the atmosphere, sound radiates unevenly in all directions. To prevent comparing the influence of one snow quality during specific meteorological conditions with another during rather different meteorological conditions, meteorological parameters such as the vertical wind and temperature gradient but also the humidity gradient need to be considered. When analysing the effect of a specific property on the SPL at only one point, this also needs to be taken into account in order to make the result comparable. Therefore, $\Delta L$ was analysed for different meteorological conditions represented by $\Delta c_{eff}$. The four snow qualities were found to have different effects on $\Delta L$. This might be explained by differences in the microstructure of the snow that causes differences in the flow resistivity of the snow. The lowest $\Delta L$ was found for dry snow, which corresponds well with the findings of Embleton et al.\textsuperscript{23} and Albert\textsuperscript{22} who present lower flow resistivities for dry snow than other snow types. Furthermore, the two peaks of $\Delta L$ in the frequency distribution for dry snow (Figure 6) might be explained by different grain shapes. Albert\textsuperscript{22} found a flow resistivity, which was clearly lower for dry snow with spherical grains than for dry snow with flat grains.

Damp snow leads to a higher $\Delta L$ and a higher variation of $\Delta L$ than frozen snow. One possible reason might be a rather high porosity of the frozen snow compared with the more dense damp snow. However, the frequency distributions of $\Delta L$ for these two snow qualities (Figure 6) indicate a certain similarity. It may therefore be the case that damp and frozen snow are not completely delimited from each other in the classification. A possible explanation might be that this classification is based on subjective observations and only the uppermost layer of the snow pack is taken into account, but lower layers might also effect the propagating sound dependent on its frequencies.

For dry snow, $\Delta L$ is mostly negative for negative $\Delta c_{eff}$ and mostly positive for positive $\Delta c_{eff}$. The same was largely found for frozen snow. Generally, the graphs for dry and frozen snow look rather similar for $\Delta c_{eff}$ between $-0.01$ and 0.05 s$^{-1}$ if no distinction is made between occasions with and without upplega. For higher $\Delta c_{eff}$, however, $\Delta L$ is clearly greater for frozen snow. The greatest $\Delta L$ was observed for $\Delta c_{eff} \approx 0$ s$^{-1}$ and damp snow. The differences in surface properties are therefore assumed to be more important during light downward or upward bending and strong downward bending, whereas they seem to be less important for moderate downward bending. This is in line with the findings of Öhlund and Larsson\textsuperscript{7} where the dependence of $\Delta L$ on $\Delta c_{eff}$ was investigated for conditions with and without a snow cover. This in turn leads to the assumption that the effect of the snow quality on $\Delta L$ is dependent on the sound wave’s angle of incidence. $\Delta L$ is often close to zero that indicates that meteorological, ground, and other effects might cancel each other out. These findings may be somewhat limited as is indicated by the relatively high standard deviations of $\Delta L$. This might be explained by uncertainties due to the method of merging meteorological data sets originating from two locations into one, resulting in biases in $\Delta c_{eff}$. Furthermore, the already discussed uncertainties in the snow observations and classification might add additional bias.
Lower SPLs were measured when upplega was observed. Upplega adds additional volume to the vegetation that makes the interaction between sound waves and a surface more likely. That in turn enhances the effect of the snow, which can dampen or amplify the sound depending on the snow quality. The higher the frequency, the larger the difference in $\Delta L$ for occasions with/without upplega. This corresponds with Attenborough\textsuperscript{12} and Bucur\textsuperscript{13} who found that ground attenuation increases with decreasing wavelength. The relatively high deviations of $\Delta L$ may be due to the varying snow qualities but also due to uncertainties in the data as mentioned above.

$\Delta L$ is not found to be directly linked to atmospheric stability. However, stability was analysed only for the lowest 18 m. Based on the findings of Boué\textsuperscript{15} concerning stratified spreading, it is assumed that the location of the inversion would influence sound propagation. From these measurements, it is not possible to draw conclusions about the influence of the inversion height relative to the source and therefore stratified spreading cannot be investigated.

The following conclusions can be drawn:

- The impact of snow on sound propagation was found to be dependent on the snow quality. The effect of the surface properties are particularly pronounced during meteorological conditions causing light upward or downward bending or strong downward bending
- To the knowledge of the authors, upplega has been shown to have an influence on sound propagation for the first time. Its overall effect leads to a decrease in $\Delta L$ of approximately 2 dBA compared with conditions without upplega. This effect is frequency-dependent and is more pronounced for higher frequencies.
- The importance of including meteorological processes in sound propagation studies is emphasized. In particular, the vertical wind and temperature gradient as well as the snow conditions are crucial for understanding sound propagating from elevated sources.

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