Effects of different meteorological conditions on wind turbine noise

Tom Evans (1) and Jonathan Cooper (1)

(1) Resonate Acoustics, 97 Carrington Street, Adelaide, Australia 5000

ABSTRACT

The accuracy of wind turbine noise predictions is sometimes the subject of debate during assessments of proposed wind farms. Theoretical questions are raised about the potential effects of different meteorological conditions on noise emission and propagation. In particular, periods of higher wind shear, temperature inversions and inflow turbulence have been raised as concerns. This paper presents noise measurement data gathered at operational wind farm sites where the meteorological wind shear, temperature gradient, turbulence and inflow angle variables are monitored. The effect of these factors on both noise emission and noise propagation from modern wind turbines are investigated and it is found that there is only a small influence on noise emission and negligible influence on noise propagation for the range of operating conditions of typical wind farms. An increase in noise emission was identified at lower frequencies when a turbine was operating under inflow turbulence but this only occurred at low wind speeds with no difference observed when the wind speed increased. Noise propagation from wind turbines was not found to increase with either wind shear or temperature gradient. It is theorised that this may be due to the height of the noise source as well as the fact that the operation of turbines would disrupt stable conditions immediately downwind of the blades.

INTRODUCTION

Wind energy is likely to form a major part of Australia achieving its Renewable Energy Target. According to the Clean Energy Council (2013), a considerable number of wind energy projects with a capacity of approximately 14 GW are in the planning stage.

Noise is a common community concern during planning assessments for wind farms, and the accuracy of wind farm noise predictions is sometimes questioned. This can include theoretical questions regarding the accuracy of noise predictions under certain meteorological conditions, such as higher wind shear, temperature inversions and turbulence (Hansen, 2013).

The authors have previously shown that prediction methods used for wind turbine noise provide suitable accuracy, once topography effects are accounted for (Evans & Cooper, 2012). While conditions such as wind shear and temperature inversions are known to increase noise propagation downwind from sources near ground height, it is not clear what effect they have on wind turbines typically located much higher above the ground.

This paper considers measurements undertaken at turbines and at locations near wind farms at a similar distance to that at which residences are typically located. Data regarding wind shear and temperature gradient at the sites is used to assess the effect of these conditions on wind farm noise emission and propagation. The influence of turbulence and inflow angle on noise emission is also reviewed at the sites.

BACKGROUND

Meteorological effects such as high wind shear and temperature inversions are known to influence noise propagation from noise sources at standard height. A brief review is provided here.

Wind shear

Wind shear refers to the change in wind speed with height. An equation used to approximate wind shear at a site is the empirically developed power law, given by Equation (1).

$$V_1 = V_2(H_1/H_2)^{\alpha}. \tag{1}$$

Where V_1 and V_2 refer to the wind speed at H_1 and H_2 respectively, and α is the power law exponent.

Typical average daytime values of the power law exponent range from 0.1 over smooth, hard ground to 0.4 in urban areas with tall buildings (Ray, Rogers and McGowan, 2006). Wind shear is highest during stable atmospheric conditions (Sathe and Bierbooms, 2007).

The propagation of sound downwind from sources such as traffic has been found to increase under periods of higher wind shear, due to the refraction of sound waves back towards the ground (Foss, 1978). It is not clear whether wind shear would have the same effect on the propagation of wind turbine noise, as the source is located at a significantly increased height, typically 80 m above ground.

Kochanowski (2010) suggested that the South Australian guidelines for wind farm noise (SA EPA, 2009) “do not give consideration to the effect of atmospheric stability on the noise propagation”. However, Søndergaard (2012) found that wind shear was “without any real influence” on noise propagation from wind turbines under Danish conditions.

It has also been theorised that higher wind shear may result in a different level or character of the noise generated by wind turbines, including a higher level of amplitude modulation, due to a greater differential between wind speeds at different points along the path of the blade (Van den Berg, 2006; Bowdler, 2008).

Temperature gradient

The temperature gradient in an atmosphere refers to the change in temperature that occurs with change in height above ground. Typically, near to the ground, the gradient is negative as temperature decreases as height increases (temperature lapse). Under certain conditions, temperature inversions may occur as the temperature increases with height.

Temperature inversions are known to increase noise propagation for sources near the ground. The mechanism for this is that the increasing speed of sound in warmer air causes the sound rays to refract in a similar manner to wind shear, although this occurs in all wind directions under a temperature inversion rather than just downwind (Tonin, 2012). However, to the authors' knowledge, there is little or no empirical data that suggests that temperature inversions result in increased noise propagation from wind turbines. The increased height of the noise source may result in a different effect under inversions.

Temperature inversions occur under stable atmospheric conditions, most often at night time. As they both occur under stable conditions, temperature inversions and periods of higher wind shear may occur simultaneously.

Turbulence

Turbulence describes small-scale, irregular air motions that results in a mixing of the atmosphere. In terms of wind turbines, it is important to distinguish between naturally occurring atmospheric turbulence and inflow turbulence resulting when a turbine is immediately downwind of another turbine.

Atmospheric turbulence reflects unstable conditions and therefore occurs under the opposite conditions to higher wind shear and temperature inversions. Due to the mixing within the atmosphere, turbulence is not normally associated with increased noise propagation. However, it has been suggested that there will be a "likely increase in turbine noise levels when they are operating in a turbulent atmosphere or in the wake of other turbines" (Hansen, 2013).

It is important to note that wind turbine site selection and design aims to avoid turbulent atmospheres and minimise the effect of inflow turbulence wherever possible, in order to maximise power generation and minimise unsteady loading on the turbine blades. Despite this, this paper discusses the influence of inflow turbulence on wind turbine noise emission and propagation.

Turbulence intensity can be used to describe the level of turbulence in the air. Turbulence intensity (I) is calculated as per Equation (2), with increasing turbulence intensity indicating increased turbulence.

$$I = u/U. \qquad (2)$$

Where u is root-mean-square of the turbulent velocity locations and U is the mean velocity.

Inflow angle

Inflow angle refers to the deviation from the horizontal of the wind flow. Inflow angle may be a factor when wind turbines are located on ridges due to the flow of the wind across the underlying terrain. Wind turbines are typically designed and sited for inflow angles of ±8° as increasing inflow angles result in reduced power output (GL Garrad Hassan, 2011).

WIND SHEAR

Noise emission with wind shear

Changes in noise emission from wind turbines have been assessed at two wind farm sites designated Site A and Site B. The turbines at both sites are modern turbines, with the blades upwind of the tower, rated at 2 to 3 MW.

Site A is a wind farm located on a flat site, with the turbines set out in a grid like manner. A Class 1 sound level meter was located near the base of one of the turbines at the edge of the wind farm. $L_{eq,1min}$ sound pressure levels were measured on an acoustically reflective groundboard for a period of 10 days. Hub height 10-minute average wind speed and direction data was measured at the turbine.

Wind shear was determined at Site A using wake-free wind speed data obtained from a set of meteorological masts at the site. Wind speeds were measured at multiple heights up to hub height and used to determine an average wind shear power exponent for every 10-minute period up to hub height.

Analysis of measured sound pressure levels was undertaken for periods when the wind direction at the turbine was within 30° of downwind with respect to the measurement location, and in integer wind speed bins. The measured A-weighted and one-third octave band sound pressure levels from 10 Hz to 10 kHz were energy averaged for different wind shear values. The measured sound pressure levels were background corrected using measurements conducted with the tested turbine turned off.

Figure 1 presents the energy averaged measured downwind A-weighted L_{eq} sound pressure levels with hub height wind speed and wind shear measured at the Site A turbine. As would be expected, it can be seen that there is a relatively strong relationship between hub height wind speed and measured sound pressure level. Generally there does not appear to be a strong increase in A-weighted noise levels with wind shear at specific wind speeds, with the exception of hub height wind speeds of 9 to 10 m/s.

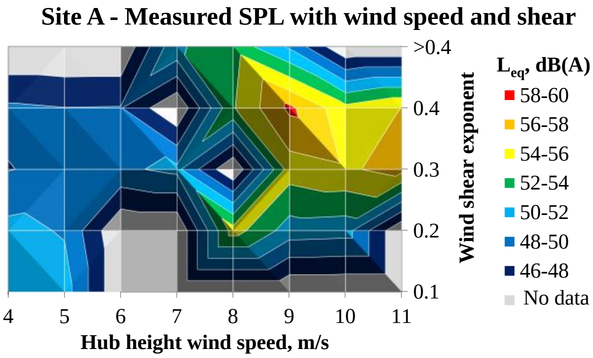

Figure 1. Average A-weighted SPL at Site A turbine with hub height wind speed and wind shear

Further investigation was undertaken on the measured sound pressure levels at these higher wind speeds and it was found that the increase in A-weighted sound pressure was related to a marked increase in noise levels at frequencies of 2 to 8 kHz under some wind shear conditions. Audio files captured at the turbine were reviewed and it was found that these higher noise levels were a result of bird noise rather than wind turbine noise.

As an example, Figure 2 presents the average sound pressure level at the Site A turbine under different wind shear power law exponents, for a hub height wind speeds of 9 m/s. This marked increase in bird noise at higher frequencies is evident for a wind shear exponent of 0.4.

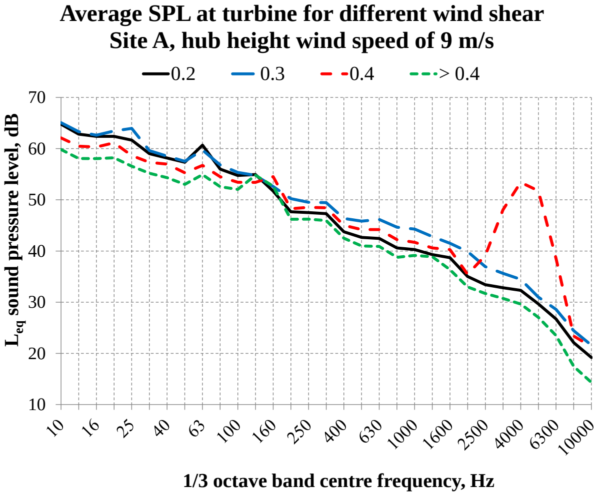

Figure 2. Average SPL at Site A turbine for different wind shear values and hub height wind speed of 9 m/s

At other frequencies, the comparison of average noise levels under different wind shear conditions indicates that there is no clear relationship between the two. In fact, low frequency noise levels were approximately 5 dB higher up to 125 Hz under the lower wind shear conditions. Similar results were obtained for other hub height wind speeds up to 11 m/s at Site A.

Site B is a wind farm located on a ridgeline, with the turbines set out in a line along the ridge. Measurements were conducted at a turbine in accordance with the requirements of IEC 61400-11 Edition 2.1 (IEC, 2006). $L_{eq,1min}$ sound pressure levels were measured on an acoustically reflective groundboard for a period of approximately 24 hours, with the measurement position moved as necessary to maintain it downwind (±15°) of the turbine. One-minute average wind speed data was determined from the power output of the turbine.

At Site B, wind shear was determined using a SODAR machine installed upwind of the turbine during the measurements. The SODAR machine provided 10-minute average measurements of wind speed, turbulence intensity and inflow angle at a range of heights between 40 and 120 metres above ground. Average wind shear values were determined for each 10-minute period based on the data between these heights. Note that the SODAR machine was located far enough away from the noise measurement location that the higher frequency noise generated by the SODAR machine did not affect the measurement results.

Figure 3 presents the energy averaged measured downwind A-weighted L_{eq} sound pressure levels with hub height wind speed and wind shear measured at the Site B turbine. There is little variation in noise emission with wind shear for given hub height wind speeds, with any variation less than 1 dB(A).

Figure 4 presents the average sound pressure level at the Site B turbine under different wind shear power law exponents, for a hub height wind speed of 5 m/s. The measured sound pressure levels were background corrected using measurements conducted with the turbine turned off.

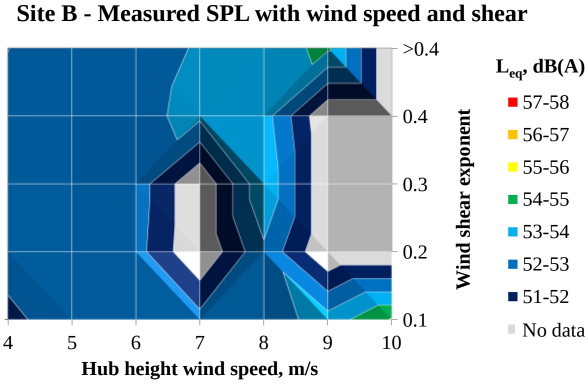

Figure 3. Average A-weighted SPL at Site B turbine with hub height wind speed and wind shear

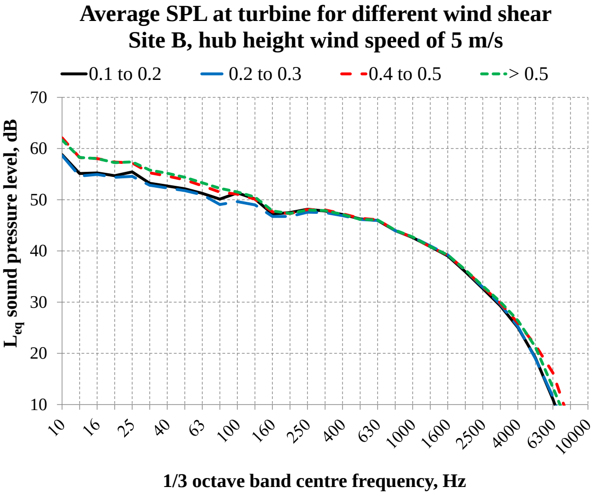

Figure 4. Average SPL at Site B turbine for different wind shear values and hub height wind speed of 5 m/s

The measurement results at Site B indicate that there is an increase of 2 to 4 dB in measured sound pressure levels at frequencies below 100 Hz for the higher shear conditions. There is negligible difference in sound pressure levels with shear for frequencies above 100 Hz.

Similar results were obtained at the Site B turbine for wind speeds of up to 8 m/s. No conclusion could be drawn at higher wind speeds for Site B as higher wind shear conditions did not occur at these speeds during the survey.

The measurements at the Site B turbine suggest there may be a marginal increase in noise levels at frequencies below 100 Hz with wind shear for hub height wind speeds of 8 m/s and below. However, this was not the case at Site A, suggesting that other variables may explain the difference.

It is also important to note that turbine noise levels at the nearest houses, typically located 1 to 2 km away, are normally controlled in the 200 to 800 Hz range, so a relatively minor increase at lower frequencies is unlikely to alter the overall A-weighted turbine noise levels at a residence.

Noise propagation with wind shear

The experience of the authors in conducting measurements of wind farm noise at residences suggests that wind shear does not substantially influence noise propagation from wind turbines. This is most evident when comparisons of measured noise levels during the day (relatively lower wind shear) are compared to those at night (relatively higher wind shear).

Figure 5 provides an example of this for a measurement location approximately 1.5 kilometres away from a wind farm on a ridgeline (Site C). The measured downwind (±45°) weighted wind farm noise levels with wind speed are presented for the wind speed range over which turbine noise levels controlled the measurement result, for both the day and night time periods. Night has been taken as 10 pm to 7 am.

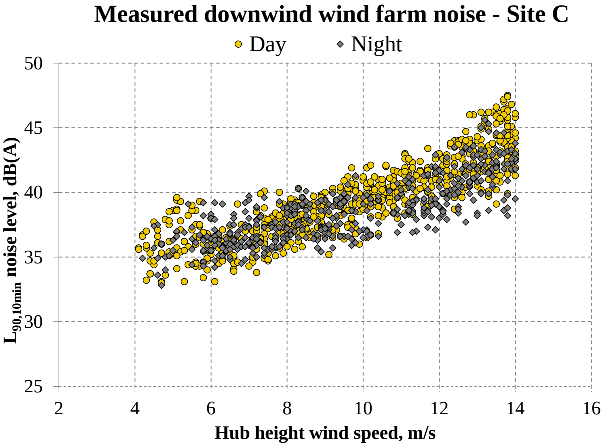

Figure 5. Measured downwind wind farm noise levels at 1.5 km from Site C for day and night periods

For the majority of the wind speed range, no change is observed between the day and night time periods. It is expected that wind shear at night is higher than during the day so the lack of change suggests that wind shear does not influence noise propagation. Note that the fact that daytime levels are slightly higher at a wind speed of 13 to 14 m/s is likely due to a higher wind speed at ground level (i.e. lower wind shear) resulting in comparatively more background noise at the monitoring site than during the night.

A more detailed analysis was undertaken based on measurements conducted at a location approximately 700 m from the nearest turbine at Site A. Figure 6 presents the measured A-weighted noise levels with wind speed under downwind (±45°) conditions for the wind speeds over which the turbines operate up to those at which they reach their maximum sound power level. Note that the relationship between measured noise levels and wind speed in Figure 6 follows the relationship between sound power levels of the turbines with wind speed, demonstrating that the dataset is typically controlled by turbine noise.

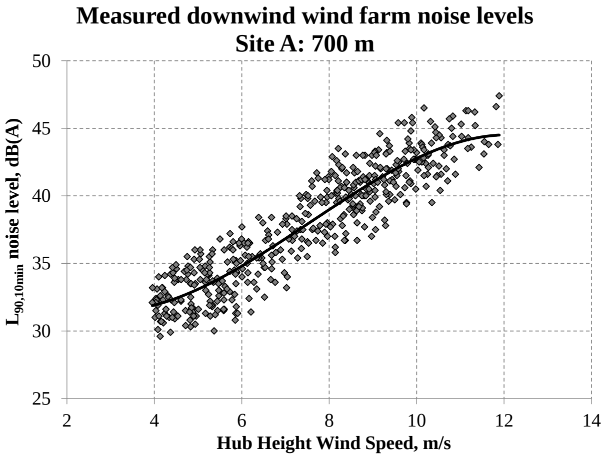

Figure 6. Measured downwind wind farm noise levels at location 700 m from Site A

A third-order polynomial trendline was fitted to the data in Figure 7, with the deviation of each data point from the trendline calculated and plotted against the calculated wind shear at the time from the relevant meteorological mast. Figure 6 presents the deviation in measured noise levels from the trendline with wind shear. Note that the trendline and deviation have only been calculated based on hub height wind speeds up to 8 m/s, as a reasonable spread of wind shear values were observed for each wind speed. Above 8 m/s, low wind shear measurements were the dominant shear condition in the data set.

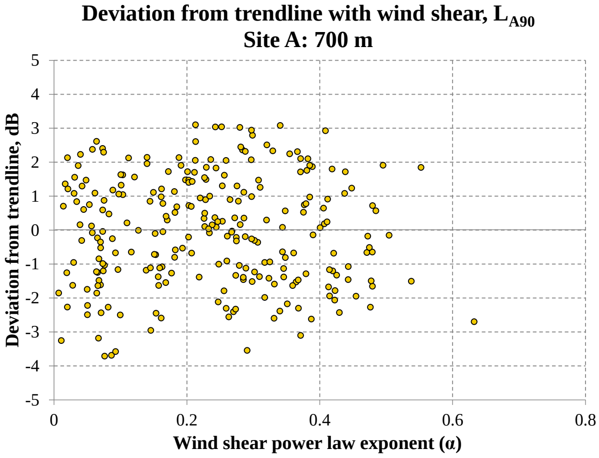

Figure 7. Deviation in measured L_{A90} noise level from trendline with wind shear at location 700 m from Site A

If wind shear influenced noise propagation from the turbines, it would be expected that deviation would increase (either positively or negatively) with wind shear exponent. The results shown in Figure 7 indicate that wind shear had little or no influence on the deviation from the trendline and therefore on noise propagation from the turbines.

Figure 8 presents a similar analysis to that shown in Figure 7 but conducted on a dataset collected at a site approximately 1.6 kilometres from the nearest turbine at Site A. At this site, one-third octave band measurements were conducted and therefore the analysis has been conducted on measurements in the 100 Hz one-third octave band rather than the overall A-weighted levels. The 100 Hz one-third octave band was selected as it was not influenced by wind-induced noise over the wind speed range considered (up to 8 m/s at night time only) and wind turbine noise was found to typically control noise levels in this range for downwind night time conditions.

While a relatively limited dataset was collected at this location, it appears that wind shear did not significantly affect wind turbine noise propagation over the 100 Hz one-third octave band based on the results presented in Figure 8.

Amplitude modulation with wind shear

An assessment of amplitude modulation undertaken at a residence located approximately 1.6 kilometres from the nearest turbine at Site A is detailed in the authors' other paper presented at this conference (Cooper & Evans, 2013). This study analysed amplitude modulation based on 100 ms L_{eq} noise level measurements both on an overall A-weighted basis and in each one-third octave band against the assessment criteria detailed in New Zealand Standard NZS 6808:2010 (Standards New Zealand, 2010).

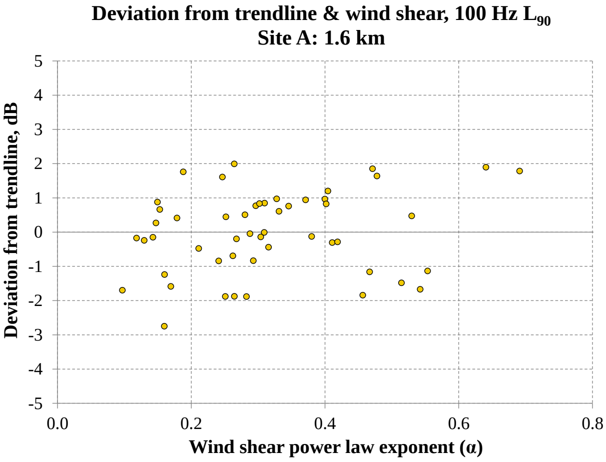

Figure 8. Deviation in measured L_{90} noise level in 100 Hz one-third octave band from trendline with wind shear at location 1600 m from Site A

The study found a limited number of occurrences of excessive amplitude modulation at night, which accounted for less than 0.5% of the total measurement period. While these occurrences did occur at night, when wind shear would typically be higher, there was no correlation between the occurrence of excessive amplitude modulation and the corresponding wind shear exponent determined from the meteorological mast at the site. Rather, it appeared that the measurements primarily occurred during periods of low background noise, which were more common at night (Cooper & Evans, 2013).

In the same study, further analysis was undertaken of amplitude modulation at the turbine itself and it was found that there was only a very minor increase in peak to trough amplitude modulation with wind shear of approximately 0.6 dB.

This finding suggests that wind shear is not a primary determinant of the level of amplitude modulation in the noise emission from the turbines at Site A.

Wind shear and background noise

While the previous analysis suggests that wind shear does not substantially influence either wind turbine noise emission or propagation, it should be recognised that it can play a key role in the perception of wind farm noise. A higher wind shear will result in lower wind speeds at receiver locations relative to the hub height wind speed controlling the turbine sound power level. This lower wind speed will result in lower background noise levels at receiver locations, making the turbine noise more prominent to a listener than it would be during a low wind shear period.

It is important to note that current noise criteria applied to wind farms and other noise sources in Australia do not generally require inaudibility to be achieved. Rather, they are normally set for each wind speed as the higher level of:

- a base limit, typically 35 or 40 dB(A), or
- the background noise level + 5 dB(A).

The background noise level is determined by fitting a polynomial trendline to the measured $L_{90,10min}$ noise levels with hub height wind speed. This may be determined for all time periods, but may also be determined separately for night time periods. Potential variations in wind shear during a background monitoring period will result in a greater spread of background noise levels. Measurement campaigns carried out to determine background noise levels for criteria during different periods of shear could therefore result in different criteria being set for a wind farm, assuming this shear was sustained for a period of time.

This does not necessarily mean that compliance will not be achieved with the noise criteria under higher wind shear. Higher wind shear is typically confined to stable atmospheric conditions and lower wind speeds. Therefore, any periods of lower background noise levels would also typically be restricted to these lower wind speeds. Figure 9 presents the wind shear values determined at the meteorological mast at Site A plotted against hub height wind speed. There is considerable variation in wind shear at wind speeds below approximately 8 m/s but little variation at higher wind speeds.

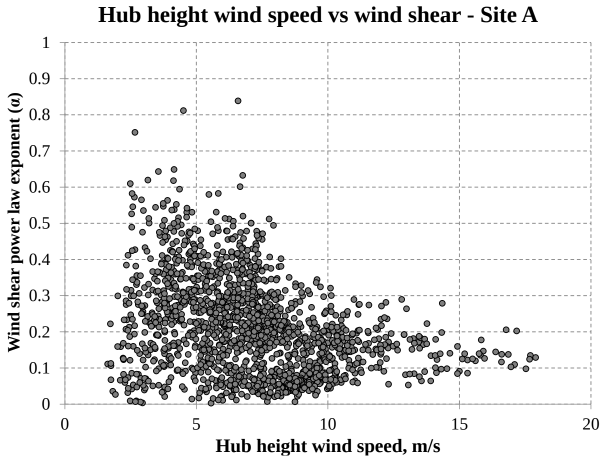

Figure 9. Wind shear values with hub height wind speed at Site A

This suggests that, for Site A, as long as the wind farm noise level remains below the relevant base limit (35 or 40 dB(A)) up to a wind speed of 8 m/s, then the influence of wind shear on compliance with the desired noise levels would be minimal. Should the base limit be exceeded at a wind speed below 8 m/s, then the influence of wind shear on background noise levels may need to be considered at Site A. In this case, it may be appropriate to analyse how often high shear periods occur and consider their influence on background noise levels in order to determine the background + 5 dB(A) criterion. Note that wind shear was not an issue for compliance at Site A as wind turbine sound levels did not exceed the base limit at any hub height wind speed.

Generally, as wind shear does not appear to substantially affect the level of wind turbine noise at a receiver, then the noise criteria would still be achieved as long as the minimum criteria is met for those wind speeds at which higher shear conditions are observed in the environment.

TEMPERATURE GRADIENT

Noise emission with temperature gradient

Although temperature gradient was not expected to influence noise emission from wind turbines, a review was carried out based on measurements conducted at the turbine at Site A. The meteorological masts at the site recorded 10-minute average temperature gradient from the bottom to the top of the mast. No change in downwind noise emission was observed at the turbine under standard temperature gradient (temperature lapse) relative to that under a temperature inversion for wind speeds between cut-in and rated power.

Noise propagation with temperature gradient

Noise propagation from wind turbines under different temperature gradients was considered based on the measurements conducted at the location 700 m from the nearest turbine at Site A, as the meteorological masts recorded temperature gradient for each 10-minute period. The measured downwind wind farm noise levels at this location have been presented in Figure 6.

In a similar manner to that used to consider wind shear, the deviation from the polynomial trendline was analysed against the average 10-minute temperature gradient. Figure 10 presents the deviation from the trendline with temperature gradient, with a negative gradient representing a temperature lapse and a positive gradient representing a temperature inversion. Note that the trendline and deviation have only been calculated over wind speeds up to 8 m/s as temperature inversions did not occur at wind speeds above this, as shown in Figure 11 (presenting the entire dataset for all wind directions during a monitoring period of six weeks).

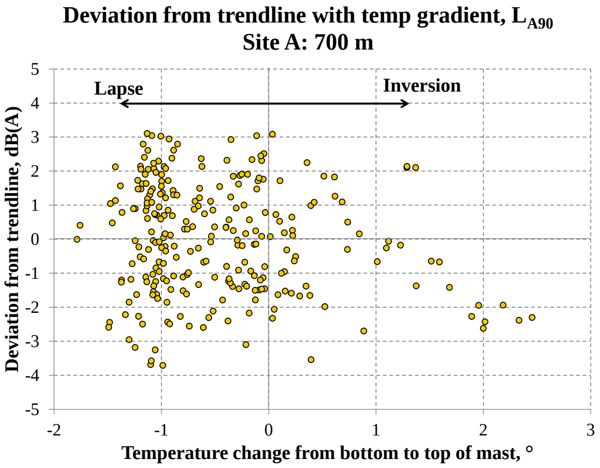

Figure 10. Deviation in measured noise level from trendline with temperature gradient at location 700 m from Site A

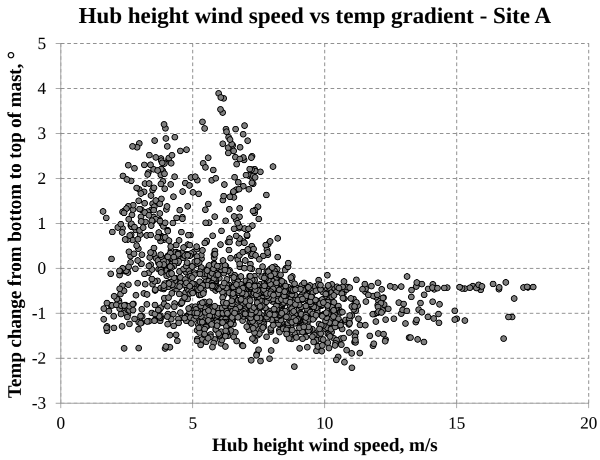

Figure 11. Temperature gradients with hub height wind speed at Site A

The results presented in Figure 10 indicate that there was no increase in noise propagation under temperature inversions. In fact, it the dataset may be suggestive of a marginal decrease in noise propagation under higher temperature inversions.

As was undertaken for wind shear, an analysis was undertaken on change in low frequency noise propagation with temperature gradient at a site approximately 1.6 kilometres from Site A where one-third octave band measurements had been conducted. Figure 12 presents the deviation in measured noise levels in the 100 Hz one-third octave band from the trendline for downwind night time conditions. Although it is based on a relatively limited dataset, the analysis presented in Figure 12 suggests that there is a negligible influence of temperature gradient on the propagation of wind turbine noise in the 100 Hz one-third octave band.

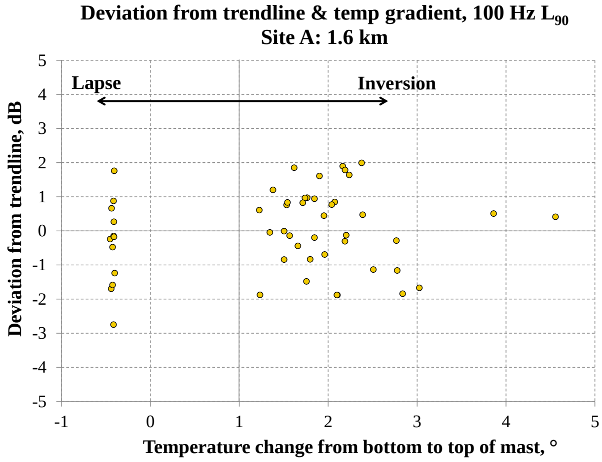

Figure 12. Deviation in measured L_{90} noise level in 100 Hz one-third octave band from trendline with temperature gradient at location 1600 m from Site A

Temperature gradients and background noise

It should be noted that temperature inversions will typically occur during more stable conditions when wind shear is also higher. Therefore, background noise levels at receiver locations will be relatively lower under temperature inversions for the same given hub height wind speed. This could have an important influence on the perception of wind turbine noise as previously discussed for wind shear.

For Site A, this effect will be limited to relatively low hub height wind speeds as shown in Figure 11. This suggests that, as long as the minimum base criterion is achieved at a hub height wind speed of 8 m/s, these low background noise levels will not impact on the site achieving compliance with the noise criteria.

TURBULENCE

Noise emission with atmospheric turbulence

Measurements conducted at the turbine at Site B were used to review the potential effects of atmospheric turbulence on noise emissions, based on 10-minute average turbulence intensity recorded at hub height by the SODAR machine.

Figure 13 presents the energy averaged measured A-weighted L_{eq} sound pressure levels with hub height wind speed and atmospheric turbulence intensity (from 5% to 20%) measured immediately upwind of the turbine. There is no relationship between the turbulence intensity and noise emission from the turbine.

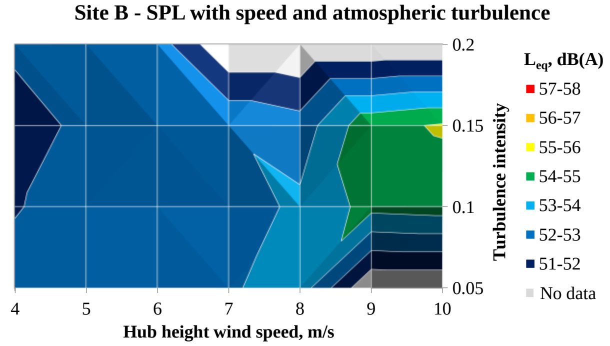

Figure 13. Average A-weighted SPL at Site B turbine with hub height wind speed and atmospheric turbulence intensity

Figure 14 presents the average sound pressure level from 20 Hz to 8 kHz at the Site B turbine under different turbulence intensities, for a hub height wind speed of 5 m/s. The measured sound pressure levels have been background corrected based on measurements conducted with the turbine not operating, with data below 20 Hz not presented as it was controlled by background noise. A hub height wind speed of 5 m/s is presented as a reasonable range of data points was obtained for the different turbulence intensity values.

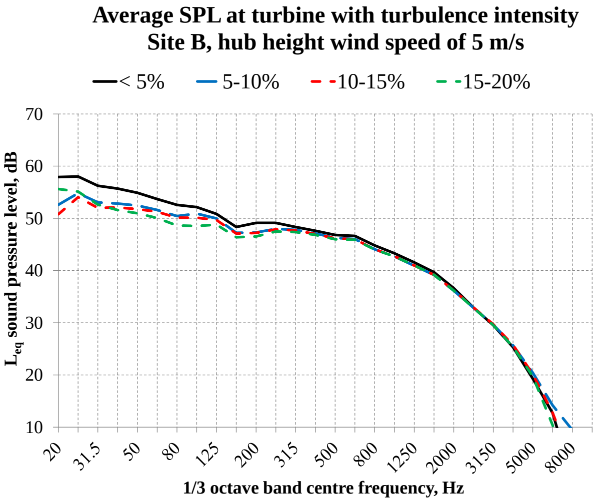

Figure 14. Average SPL at Site B turbine for different turbulence intensity at a hub height wind speed of 5 m/s

The data presented suggests that there is not any noticeable increase in sound pressure level at the turbine with increasing turbulence intensity. In fact marginally higher sound pressure levels were measured under low atmospheric turbulence at low frequencies, although this is most likely a result of natural variation at these frequencies.

Similar results to those presented in Figure 14 were obtained for hub height wind speeds of up to 10 m/s, indicating that atmospheric turbulence intensity did not influence noise emission at Site B.

While measurements were only obtained under turbulence intensity values of up to 20%, it is important to note that international standards prescribe allowable atmospheric turbulence levels for wind farm sites in order to ensure wind turbine life conditions are met (GL Garrad Hassan, 2011). This results in a limit of 20-25% at hub height wind speeds above approximately 6 m/s. Therefore the gathered data at Site B is considered representative of the typical range of wind farm operating conditions.

Noise emission with inflow turbulence

Inflow turbulence differs from atmospheric turbulence in that it occurs as a result of neighbouring turbines rather than meteorological conditions. As for atmospheric turbulence, inflow turbulence is typically managed during the design of the site. This is achieved by spacing turbines appropriately to improve energy generation and minimise unsteady loading on the blades of downwind turbines.

A previous study by the authors investigated the influence of inflow turbulence on noise emission from wind turbines spaced approximately 3.7 turbine diameters apart (Cooper & Evans, 2012). It was found that, when a turbine was in the wake of another turbine, there was a potential marginal increase in sound power levels of approximately 1 dB(A) but only for relatively low hub height wind speeds where the turbine was operating well below rated power. This increase is potentially compensated for by a reduction in the wind speed at the turbine due to the wake of the upstream turbine.

Further analysis of this data found that the increase under turbulent inflow conditions included an increase in low frequency noise emissions from the turbine for frequencies of approximately 200 Hz and below for lower wind speeds. Figure 15 presents the calculated sound power level of the turbine for 5 and 7 m/s under wake and non-wake conditions.

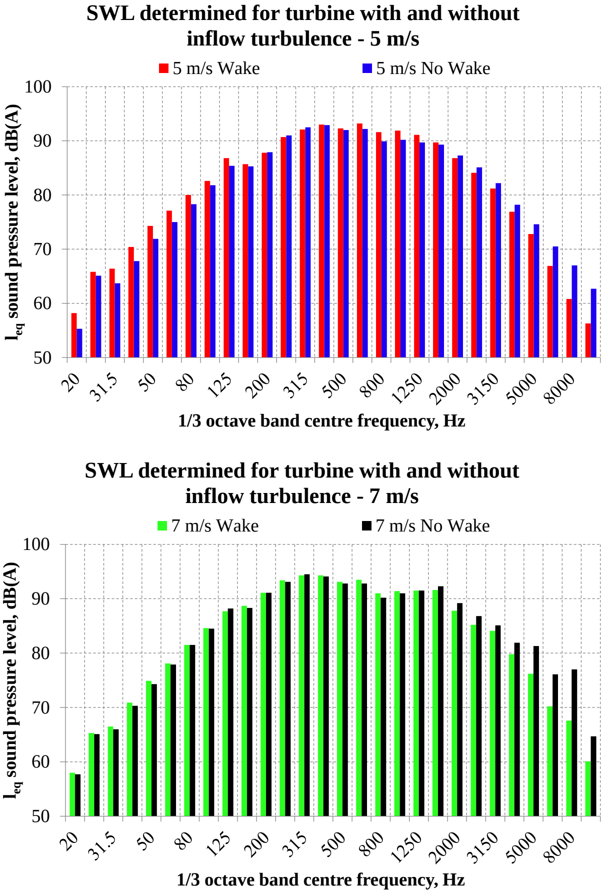

Figure 15. Calculated sound power level of turbine for 10 m height wind speeds under wake and non-wake conditions

Note that the A-weighted spectrum is presented in Figure 15 and the wind speeds are referenced to 10 m height. A wind speed of 7 m/s would correspond to a wind speed of approximately 10 m/s at hub height.

It can be seen that there is an increase in low frequency noise emission at the turbine when in the wake of another turbine (inflow turbulence) for a wind speed of 5 m/s. The increase relative to the wake-free condition was approximately 2 to 3 dB up to approximately 160 Hz. This increase was present for wind speeds of 3 to 6 m/s, but decreased from approximately 5 dB at 3 m/s to 1 to 2 dB at 6 m/s. However, the wake also appears to result in a reduction in higher frequency noise at a wind speed of 5 m/s. These findings are consistent with those of Søndergaard (2012).

As the wind speed increased, the difference in sound power level between the wake and wake-free conditions decreased such that the calculated sound power levels are the same at low frequency for a wind speed of 7 m/s. This suggests that the increase in low frequency noise levels under inflow turbulence is only relevant for relatively low hub height wind speeds. Note that the marked increase in higher frequency levels (5 kHz and above) at 7 m/s under wake-free conditions is believed to be a result of bird noise.

From the point of view of noise levels at receptor locations, this means that there may be a relatively small increase in low frequency noise levels when turbines are operating in the wake of other turbines for lower hub height wind speeds. However, this difference is likely to be compensated for by the reduction in wind speed that will occur in the wake of another turbine.

Noise propagation with turbulence

No data was gathered at Site B to determine the influence of turbulence on noise propagation. Conventional environmental noise propagation theory would suggest that turbulence is unlikely to increase noise propagation and may actually have the opposite effect. This is due to the mixing that occurs in a turbulent atmosphere.

It is important to note that the atmosphere immediately downwind of a wind turbine will always be turbulent due to the operation of the turbine itself. Therefore, our previous study of noise propagation accuracy (Evans & Cooper, 2012), which considered noise levels measured downwind of wind farms, included propagation through turbulent atmospheres. This found a reasonable degree of accuracy between predicted and measured downwind noise levels using standard noise propagation models and therefore turbulence is not believed to have a significant influence on noise propagation from wind turbines.

INFLOW ANGLE

Noise emission with inflow angle

The SODAR machine installed at Site B also collected data on inflow angle, allowing comparison of the measured noise levels under different 10-minute average inflow angles. Figure 16 presents the energy averaged measured downwind A-weighted L_{eq} sound pressure levels with hub height wind speed and inflow angle (in degrees) measured immediately upwind of the Site B turbine. There is no relationship between inflow angle and noise emission variables across the range of conditions for which data was gathered.

Figure 17 presents the average background-corrected sound pressure level from 20 Hz to 10 kHz at the Site B turbine under different inflow angles, for a hub height wind speed of 5 m/s. A wind speed of 5 m/s is presented as a reasonable range of data was obtained across different inflow angles.

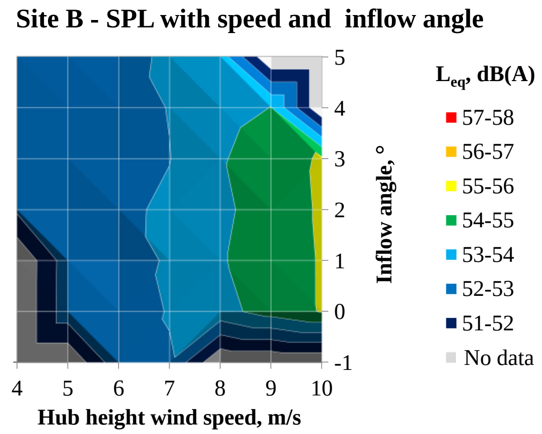

Figure 16. Average A-weighted SPL at Site B turbine with hub height wind speed and inflow angle

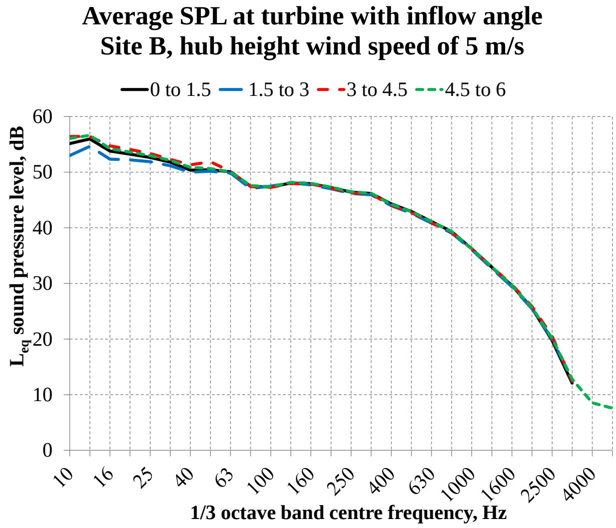

Figure 17. Average SPL at Site B turbine for inflow angles at a hub height wind speed of 5 m/s

The data presented does not show a relationship between inflow angle and noise emission. While there is a relatively small variation in measured levels at frequencies below 63 Hz, the sound pressure levels for an inflow angle of less than 1.5° are the same as for those with an angle between 4.5° and 6°.

Noise measurements were gathered at the turbine at Site B for inflow angles up to 6°. Wind farms are typically designed for inflow angles up to 8°, to reduce energy losses that occur under higher angles (GL Garrad Hassan, 2011). Therefore the gathered data at Site B is considered representative of the typical range of inflow angles for wind farms.

Noise propagation with inflow angle

No data was gathered at Site B to determine the influence of inflow angle on noise propagation. Based on the limited effect of other meteorological conditions considered so far in this study, it is theorised that there would be no significant influence of inflow angle on noise propagation from wind turbines.

DISCUSSION

The fact that downwind propagation of wind turbine noise does not appear to increase under stable meteorological conditions over distances of up to two kilometres is contrary to the known effects of these conditions on noise propagation from other noise sources.

One potential factor is that the turbulent wake downwind of an operating turbine interrupts the stable conditions, causing mixing of the atmosphere at the source. This may contribute to a reduction in the influence of stable conditions on wind turbine noise propagation in the downwind direction.

Another key factor to consider with respect to wind turbines is that, with a hub height of approximately 80 metres, the height of the noise source is significantly higher than typical environmental noise sources. At all sites considered in this paper, the wind turbine hubs are well above the height of the measurement locations, and the mean propagation height is relatively high with no shielding from source to receiver. This means that there is much less opportunity for interaction between the ground and sound from the source than would be the case for a source located at ground level.

Refraction of sound from sources under higher sound speed gradients (resulting from higher wind shear and/or temperature inversions) provides another path for sound from sources near to the ground to the receiver, increasing noise propagation. This situation may not be relevant for wind turbines where there is already an uninterrupted path from source to receiver, reducing the influence of these factors on noise propagation.

It is important to note that this theory may not apply to sites where there is intervening topography between the turbines and the measurement locations that interrupts line-of-sight. While this situation would be rare in Australia for areas where turbine noise levels may be at or approaching the noise criteria, wind shear and temperature inversions may have more influence on noise propagation in these cases.

CONCLUSION

This study into the influence of different meteorological conditions on noise emission and propagation from wind turbines has considered:

- wind shear
- temperature gradient
- atmospheric turbulence
- inflow turbulence
- inflow angle.

Based on the studied sites, these factors were not found to significantly influence noise emission from the turbines. The only factor that did influence noise emission at times was inflow turbulence, occurring when a turbine is operating in the wake of another turbine. Low frequency noise levels were found to marginally increase but this only occurred at lower wind speeds and the low frequency noise levels under inflow turbulence were found to be the same as those without inflow turbulence for a hub height wind speed of 10 m/s.

It was found that downwind noise propagation from the wind turbines was not influenced by either wind shear or temperature gradient. This is an interesting finding given the known effects of these factors on noise propagation from other sources. It is theorised that this lack of influence may be due to the turbulent wake of the turbine interrupting stable conditions as well as the height of the noise source.

Despite the lack of influence of wind shear and temperature inversions on noise propagation from turbines, it is recognised that these stable conditions would result in lower background levels at receiver locations for a given hub height wind speed and relatively increased audibility of wind turbine noise. Therefore, the wind turbine noise may seem louder to an observer under these conditions although the noise level has not actually increased.

REFERENCES

Bowdler, D, 'Amplitude Modulation of Wind Turbine Noise. A Review of the Evidence', *Institute of Acoustics Bulletin*, vol. 33, no. 4, pp. 31-35.

Clean Energy Council, 2013, *Technologies – Wind energy*, Clean Energy Council, viewed 24 June 2013 http://www.cleanenergycouncil.org.au/technologies/wind.html.

Cooper, J & Evans, T, 2012, 'Influence of upwind turbines on wind turbine sound power output', *Proceedings of Acoustics 2012*, Fremantle, 21-23 November 2012.

Cooper, J & Evans, T, 2013, 'Automated detection and analysis of amplitude modulation at a residence and wind turbine', *Proceedings of Acoustics 2013*, Victor Harbor, 17-20 November 2013.

Evans, T & Cooper, J, 2012, 'Comparison of predicted and measured wind farm noise levels and implications for assessments of new wind farms', *Acoustics Australia*, vol. 40, no. 1, pp. 28-36.

Foss, RN, 1978, *Ground Plane Wind Shear Interaction on Acoustic Transmission*, Research Project Y-1739, Washington State Department of Transportation, Olympia.

GL Garrad Hassan, 2011, *Important Wind Characteristics for Wind Farms*, prepared for Might River Power Limited, Auckland.

Hansen, C, 2013, Letter to Environmental Health Program of Victorian Department of Health, dated 23 May 2013, http://doc.wind-watch.org/Hansen-victoria-health.pdf.

IEC 2006, *Wind turbine generator systems – Part 11: Acoustic noise measurement techniques*, IEC 61400-11 Edition 2.1, International Electrotechnical Commission, Geneva.

Kochanowski, R, 2010, 'Assessment of the methods addressing atmospheric stability effects in the latest SA EPA "Wind farms environmental noise guidelines", New Zealand NZS 6808 and Australian AS 4959', *Proceedings of the 20th International Congress on Acoustics*, Sydney, 23-27 August 2010.

Ray, ML, Rogers, AL & McGowan, JG, 2006, 'Analysis of Wind Shear Models and Trends in Different Terrain', *Conference Proceedings: American Wind Energy Association Windpower*, Anaheim, 22-25 May 2006.

SA EPA 2009, *Wind farms environmental noise guidelines*, South Australian Environment Protection Authority, Adelaide.

Sathe, A & Bierbooms, W, 2007, 'Influence of different wind profiles due to varying atmospheric stability on the fatigue life of wind turbines', *Journal of Physics: Conference Series*, vol. 75, 012056.

Søndergaard, LS, 2012, 'Noise from wind turbines under non-standard conditions', *Proceedings of Internoise 2012*, New York, 19-22 August 2012.

Standards New Zealand, 2010, *Acoustics – Wind farm noise*, NZS 6808:2010, Standards New Zealand, Wellington.

Tonin, R, 2012, 'Sources of Wind Turbine Noise and Sound Propagation', *Acoustics Australia*, vol. 40, no. 1, pp. 20-27.

Van den Berg, GP, 2006, 'The sound of high winds: the effect of atmospheric stability on wind turbine sound and microphone noise', PhD thesis, University of Groningen, Groningen.