

# Proceedings of Meetings on Acoustics

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Volume 9, 2010

<http://asa.aip.org>

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**159th Meeting**  
**Acoustical Society of America/NOISE-CON 2010**  
Baltimore, Maryland  
19 - 23 April 2010  
**Session 1pNSd: Noise**

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## **1pNSd1. Calculating annualized sound levels for a wind farm**

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Modeling done for wind farms usually focuses on calculating a worst-case short term average sound level. However, the impact to homes is not simply defined by a single meteorological condition. Rather, a more complete picture of the impacts is given by calculating sound levels under various meteorological conditions that occur during the year. The actual sound level at a receiver will depend on variations in atmospheric stability, wind speed, wind direction, and other parameters that change hourly. This paper will describe a method to calculate hourly sound pressure levels for individual receivers over the course of an 8760 h year and give examples of different wind farm configurations and how they affect annualized sound levels.

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Published by the Acoustical Society of America through the American Institute of Physics

## Problem statement

- **Modeling done for wind farms focuses on a worst-case short term average sound level (Lmax)**
- **“Impacts” are not defined by a single meteorological condition or single hour**
  - **WHO 8 hr and annual guidelines**
  - **EPA annual Ldn guideline**
- **How do we characterize impacts of a source with sound emissions and propagation highly dependent on meteorology, over the course of an 8,760 hour year?**



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Sound propagation modeling for wind farms is usually done assuming a single meteorological condition – a moderate nighttime inversion, or equivalently, winds blowing from the source to the receiver. For wind farms, this is usually sufficient to estimate a typical one-hour maximum sound level. However, the actual impact to a resident is not fully described by a single condition. This is recognized by several guidelines and standards that look to multi-hour levels, like the WHO 8-hour nighttime guideline of 45 dBA (WHO 1999), the WHO Europe outdoor annual average nighttime guideline of 40 dBA (WHO Europe 2009), and U.S. EPA’s annual average Ldn guideline of 55 dBA (EPA 1974). The problem is then to try to characterize impacts from a wind farm over the course of a year. This is difficult, in that the sound emissions from a wind farm are constantly changing due to changes in wind speed and direction, and the propagation characteristics are also constantly changing.

## Outline

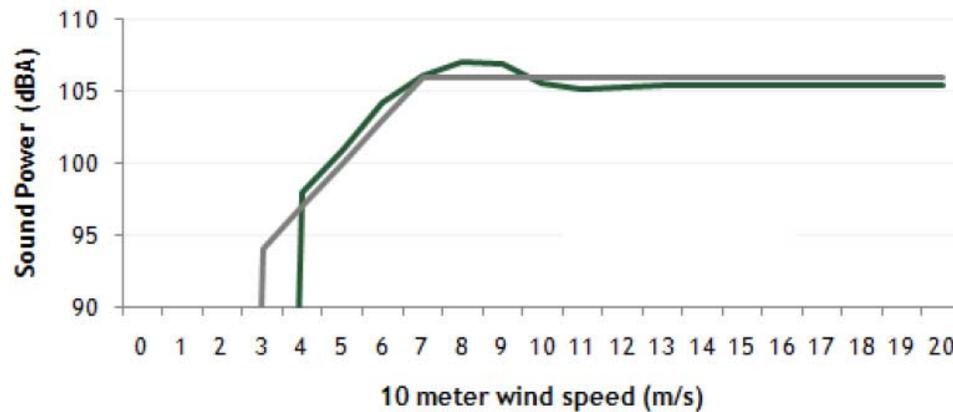
- Sound emissions from turbines
- Refresher on factors affecting downwind propagation
- Method to calculate annualized impacts
- Results from case studies

This paper looks at the changes in sound emissions of wind turbines as a function of wind speed. It then discusses meteorology and downwind propagation. Finally, we show a method to calculate hourly sound levels and annualized impacts, with examples.

## Wind Turbine Source Sound Levels

- Sound power is primarily dependent on wind speed

Sound power by wind speed for two variable speed turbines



Sound power from a wind turbine is a function of wind speed. Shown above are graphs of sound power for two different turbines. There is no significant sound below the cut-in wind speed of 3 to 4 m/s. Sound levels gradually rise after cut-in to a maximum level and approximately stay at the maximum sound emission until the cut-out wind speed of 20 to 25 m/s.

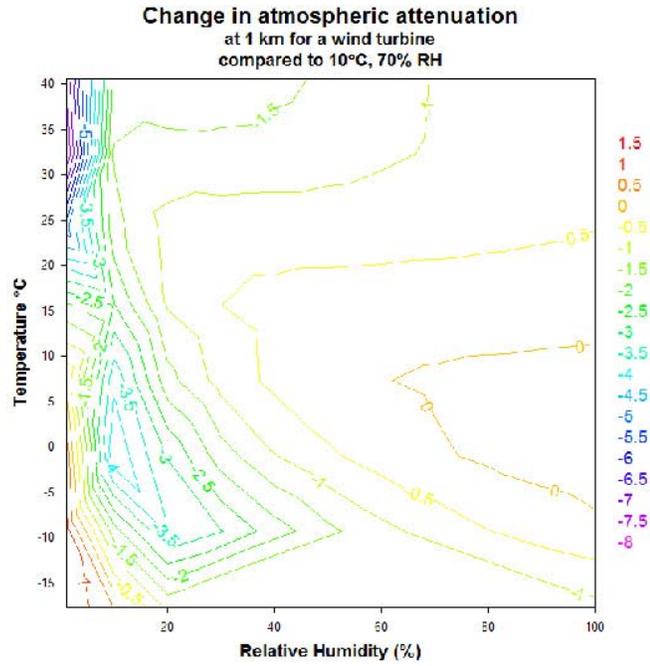
## Meteorological factors affecting propagation

- Temperature, pressure, and humidity - Sound absorption
  - Wind direction
  - Vertical wind speed gradient
  - Vertical temperature profile
  - Atmospheric turbulence
- 
- Atmospheric Stability

Sound propagation is affected by meteorology. Temperature, pressure, and humidity affect the level of sound absorbed by the atmosphere. Wind direction combined with the vertical wind speed gradient affects the refraction of sound (and to some extent, the directionality of the sound.) Temperature and turbulence also affect refraction and scattering. These latter three variables can be simplified into a term “atmospheric stability” which we will use here to simplify meteorological parameters affecting propagation.

## Atmospheric Attenuation

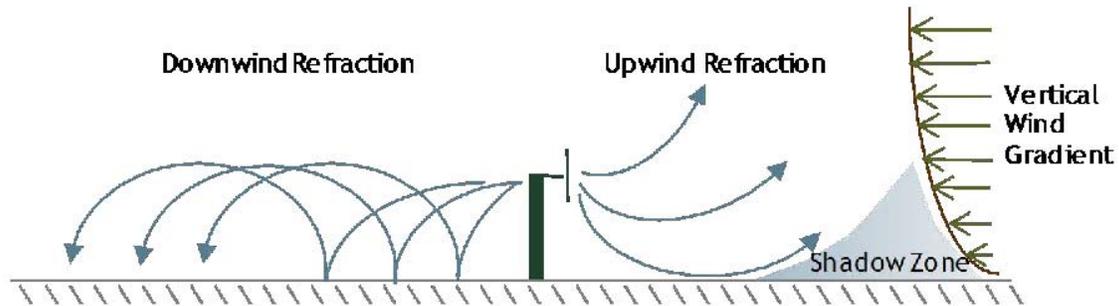
- Function of temperature humidity and pressure
- Default is to use 10°C and 70% relative humidity when modeling Lmax



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Atmospheric absorption is a function of temperature, humidity, and pressure. For wind farm modeling, we use a default of 10 degrees C and 70% relative humidity, as this generally yields the lowest attenuation (from ISO 9613-1). Other combinations of humidity and temperature yield lower sound levels due to increased atmospheric absorption. The graph above shows the additional attenuation one would get for a single wind turbine at 1 km, relative to the absorption at 10 degrees C and 70% humidity. As shown, the lowest sound levels would occur around freezing temperatures and dry conditions. The results show higher attenuation at very hot and dry conditions, but these are not typical of most landscapes.

## Refraction due to wind

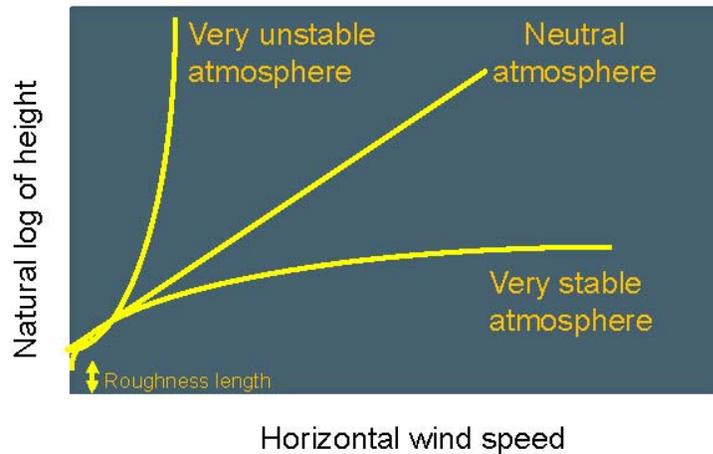


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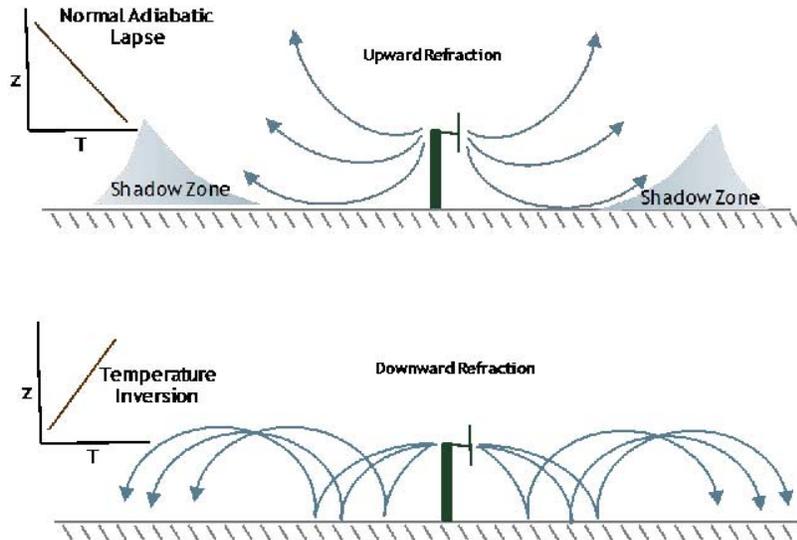
Sound refracts due to a vertical wind gradient. With winds increasing with height, as is most often the case, sound will refract downward downwind of the source and upward upwind of the source. In the upwind direction, this can lead to a shadow zone with low sound levels. Downwind, increases or decreases can be found depending on ground absorption and distance. (Crocker 2007)

## Wind profiles under various stabilities



Wind affects atmospheric stability. Very unstable atmospheres have a lot of vertical mixing and are characterized by very little layering and relatively constant wind speeds with height. At the other extreme, very stable atmospheres tend to allow layering with a higher degree of wind shear, that is, increasing wind speed with height.

## Refraction from Temperature Profile

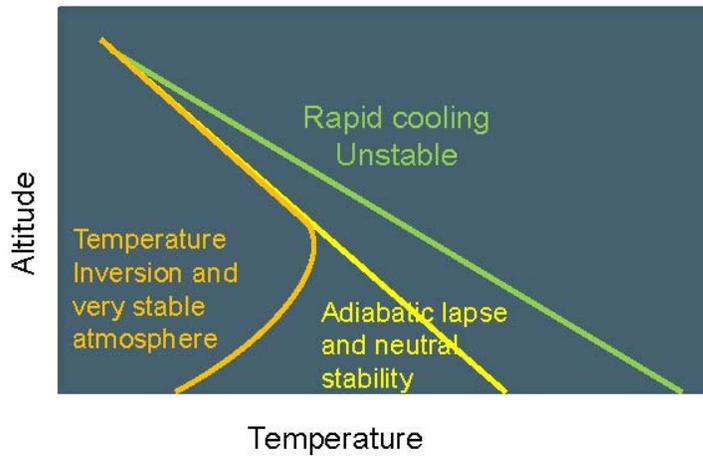


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Temperature also affects propagation. With a normal adiabatic lapse (decreasing temperature with height), sound refracts upward, creating shadow zones on both sides of the source. With a temperature inversion, which typically only occurs at night, temperature increases with height up to a point, and downward refraction occurs. (Crocker 2007)

## Vertical Temperature Profiles



An unstable atmosphere is characterized by rapid cooling, or cooling greater than the adiabatic rate. Very stable atmospheres can be created by inversions.

## Atmospheric stability

Wind Speed (m/s)	Daytime insolation (mW/cm <sup>2</sup> )				1 hr before sunset or after sunrise	Nighttime cloud cover (in eighths)		
	>60	30 to 60	<30	Overcast		0-3	4-7	8
≤ 1.5	A	A-B	B	C	D	F or G	F	D
2.0 to 2.5	A-B	B	C	C	D	F	E	D
3.0 to 4.5	B	B-C	C	C	D	E	D	D
5.0 to 6.0	C	C-D	D	D	D	D	D	D
> 6.0	D	D	D	D	D	D	D	D

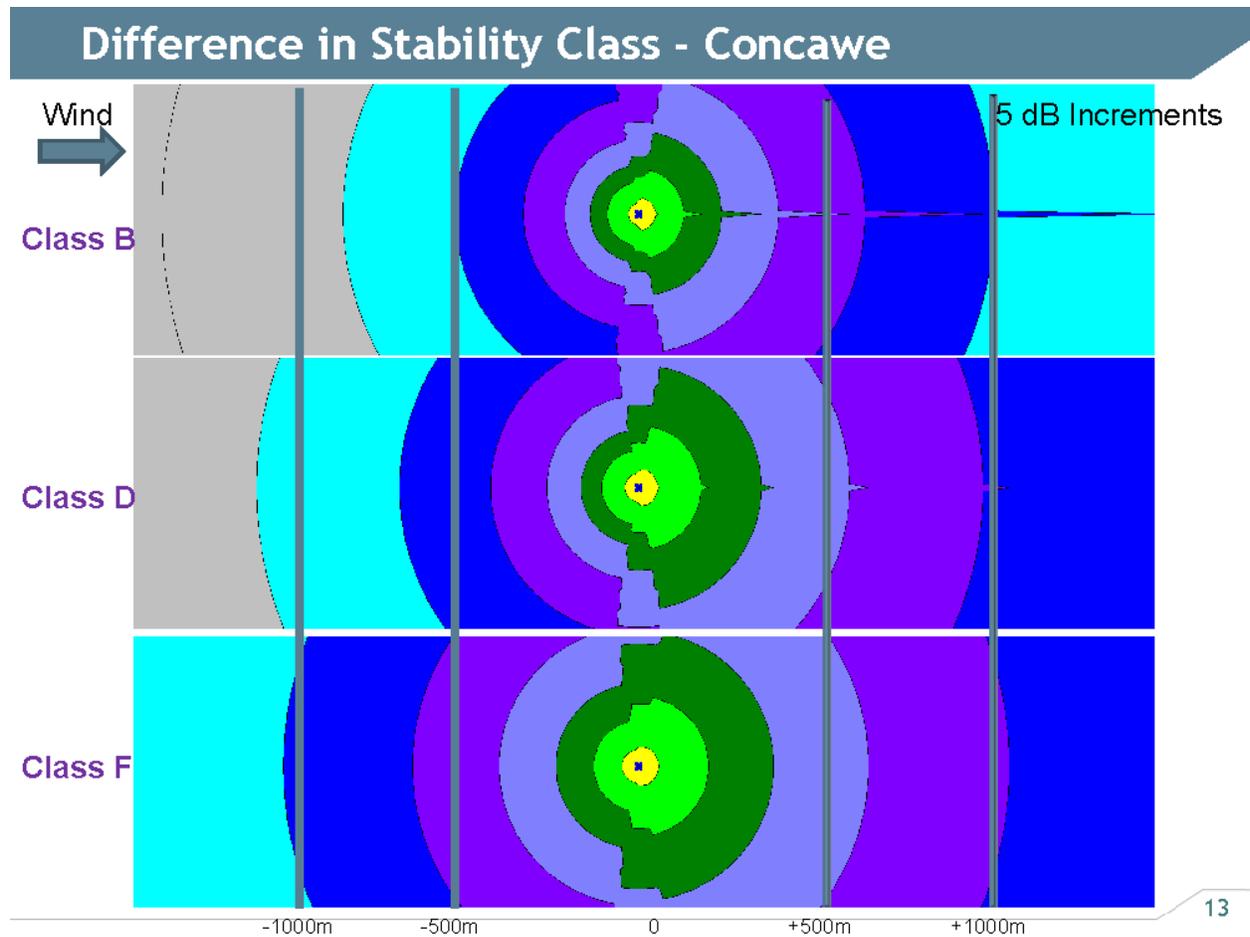
- **Pasquill Gifford stability categories**
  - Class A is highly unstable
  - Class D is neutral
  - Class F and G are highly stable
- **This allows us to combine various meteorological parameters to estimate the turbulence affecting propagation**

Pasquill Gifford stability categories have been commonly used by the U.S. EPA to characterize stability. Classes range from A to G, with A being a highly unstable atmosphere and G being very stable. The above table shows the Concawe method for categorizing different insolation levels, cloud cover, time of day, and wind speed into stability classes. (Concawe 1981)

## Stability Class

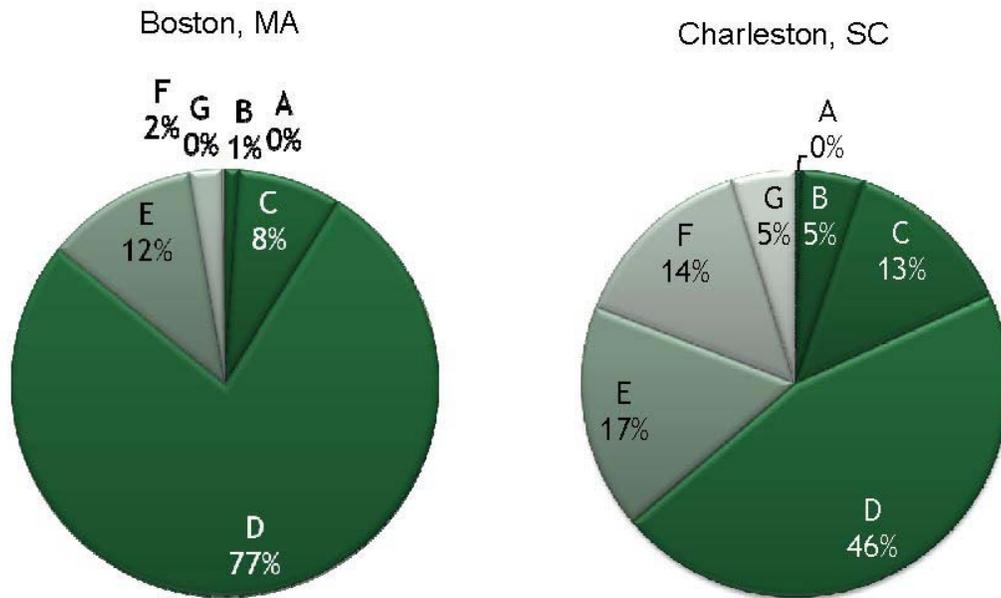
- **Unstable atmospheres are generally unfavorable to propagation**
- **Stable atmospheres are generally favorable to downwind propagation**
- **Concawe and Harmonoise give specific adjustments due to atmospheric stability**
- **ISO 9613-2 assumes a moderate nighttime inversion or downwind propagation**

According to Concawe, unstable atmospheres are generally unfavorable to propagation, while stable atmospheres are favorable. (Concawe 1981). Harmonoise, currently being developed in Europe, uses different stability characteristics developed specifically around sound propagation. (Nota, Barelds, van Maercke 2005)



The chart above shows the change in sound level according to Concawe, as modeled in Cadna A, for a wind turbine modeled as a point source with an 80 meter height, with a 3 m/s wind. As shown, increasing stability from B to D increases downwind propagation by about 5 dB. There is little change downwind from Class D to F downwind. However, upwind propagation increases more as we change from Class D to F.

## Frequency of Stability Categories



Meteorology is very site specific. If we compare Boston to Charleston, SC, we see that Boston spends most of its time in a neutral stability. However Charleston is much more varied, with both unstable and stable meteorological conditions. (Source data from US EPA Support Center for Regulatory Air Models)

## Process to annualize sound level impacts

- 1) Obtain local hourly wind speed at two or more heights, wind direction, and temperature.
- 2) Obtain cloud cover and ceiling height from the closest National Weather Service station

Now, we are ready to calculate the hourly sound levels. First, met data from the project met tower is obtained. This usually includes hourly wind speeds at multiple heights, wind direction, standard deviations, and temperature. Regional data, such as cloud cover and humidity can be obtained from the closest National Weather Service Station.

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- 3) **Calculate Stability Class following the procedure in the U.S. EPA’s “On-site meteorological program guidance for regulatory modeling applications.”**

Stability Class a function of

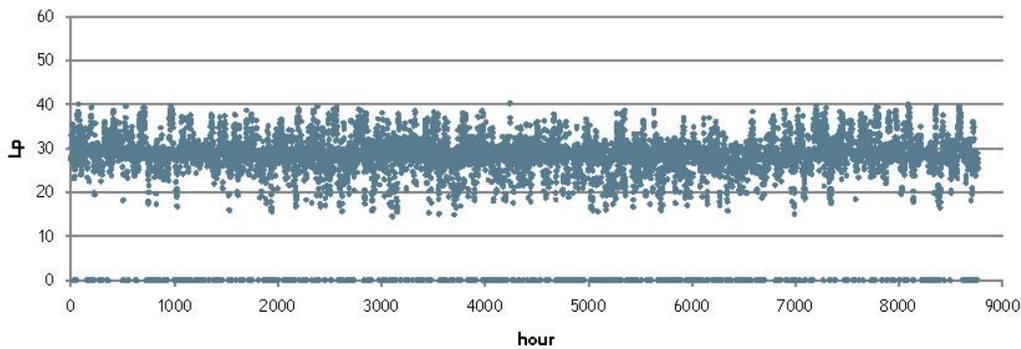
- wind speed,
- cloud cover,
- solar angle,
- daytime/nighttime, and
- ceiling height.

Step 3 is to calculate the P/G stability class. The best method is to use the US EPA’s method which takes into account wind speed, cloud cover, solar angle, daytime/nighttime, and ceiling height (EPA 1987). Other methods are available, such as looking at the standard deviation of wind direction, but these are generally less reliable.

- 4) **Run sound propagation model for 64 different combinations of wind speed, wind direction, and atmospheric stability, with Concawe meteorological adjustments**
- 5) **Match each hour's wind speed, wind direction, and stability class to those used in the model runs.**

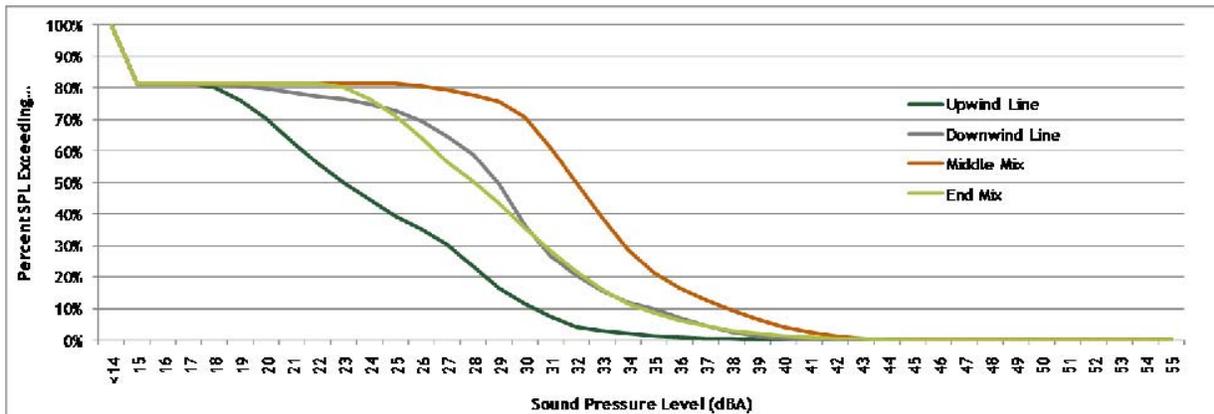
We then run the Cadna model using Concawe meteorological adjustments for 64 different combinations of wind speed, wind direction, and P/G stability class. We then look up the sound level results for each hour by matching these parameters.

- 6) Adjust sound level by wind turbine sound emissions relative to wind speed.
- 7) Account for a random normalized distribution about the mean sound power level.
- 8) Adjust for atmospheric absorption (optional)



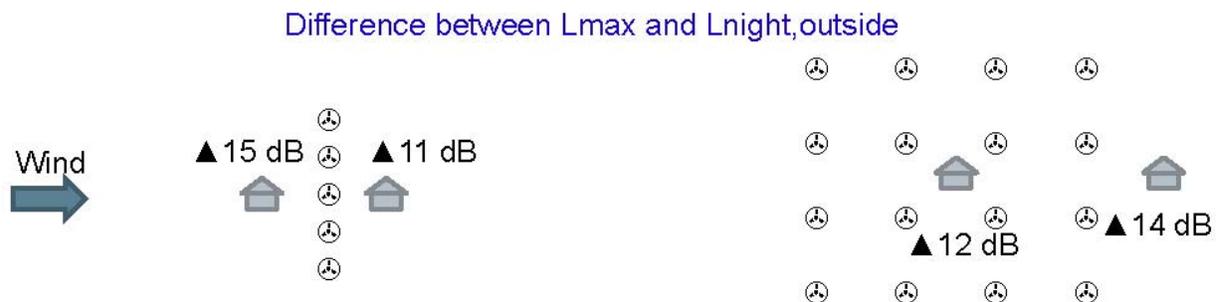
Next, we adjust the modeled sound level if the wind speed is anything other than that creating the maximum sound power. For example, if the wind speed is below the 3 m/s cut-in, the sound level is set to zero. Given that sound emissions are not fixed, but have a confidence interval, we can then randomly adjust the sound emissions using a normal distribution about the mean. In the end, we get hourly sound levels. As shown in the graph above, we see the maximum, but, in this case, sound levels are concentrated at levels that are roughly 10 dB lower than the maximum. Note that while the meteorological data used is real and the modeling results are real, we have combined the model and met data from different sites such that this example does not represent a specific place.

## ■ Cumulative frequency distribution of SPLs



The next step is to show how this data can be used. Cumulative frequency distributions can be drawn to visualize the percent of time spent at different sound levels. The steeper the curve, the less varying the sound levels. The steepest curves tend to be where the wind farm surrounds a home, with the most shallow curves from a situation where the home is upwind of the wind farm (on a prevailing basis).

- WHO Europe has new guideline of 40 dB  $L_{night, outside}$
- 40 dBA outside the home, at night, averaged over the year



- Differences are dependent of meteorology, but generally range from 5 to 15 dB.

We can also look at the difference between the  $L_{max}$  and the WHO Europe  $L_{night, outside}$  parameter (annual average nighttime sound level outside). As shown, this difference is also depending on the configuration of the home with respect to the wind farm. The differences are dependent of meteorology, but generally range from 5 to 15 dB. That is, if the modeled  $L_{max}$  is 40 dB for example, the  $L_{night, outside}$  will usually be in the range of 25 to 35 dB.

## Conclusions

- Impacts for sources such as wind turbines cannot be defined solely using  $L_{max}$
- Hourly SPLs can be estimated knowing various meteorological parameters
- The distribution of SPLs over the year can then be estimated
- Multi-hour levels can be estimated
  - $L_n$
  - $L_{night, outside}$
  - Annual  $L_{dn}$



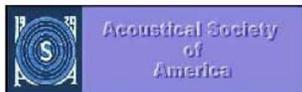
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We conclude by noting that using this technique, we can make an estimate of impacts for sources not just over one condition, but over the variety of conditions that occur over the year. With hourly sound levels, we can calculate how much time a receiver will spend at different sound levels, and calculate impacts relative to multi-hour guideline levels such as the WHO Leq for an 8-hour night, WHO Europe's 40 dB  $L_{night, outside}$  annual average, and U.S. EPA's 45 dB  $L_{dn}$ .



## Questions?

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