METEOROLOGICAL FACTORS AFFECTING ENVIRONMENTAL NOISE PROPAGATION OVER SEVERAL KILOMETRES

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Abstract

Temperature inversion and wind conditions are known to have a significant effect on noise propagation over long distances. Consideration of such conditions is a challenging part of assessing environmental noise propagation over several kilometres in environments with relatively low background noise levels. To consider these phenomena, noise consultants generally use standard commercial noise models, which apply correction factors, linear vertical approximations of the prevailing weather conditions, or assume horizontally uniform weather conditions. These assumptions, whilst not ideally reflective of real-world weather conditions will produce generally reliable assessments of noise overall, but for any specific period, these assumptions may lead to inaccurate assessments of short term noise levels. This is especially the case when there are significant spatial or temporal changes in the wind direction, wind speed or temperature in the period under consideration. As a result, the assumptions underpinning commercial noise models are not well suited to real-time or predictive/forecast management of short term noise impacts over long distances. Understanding the nature of these non-linear, time and space varying weather conditions can lead to more accurate noise assessments. Examples of temperature profile measurements and new techniques to consider these influences in a three dimensional time and space varying field are outlined, including predictive/forecasting noise modelling for management of industrial noise levels.

1. Introduction

This paper examines some of the physical phenomenal that affect environmental noise propagation over distances of several kilometres. As such, these influences may be relevant when assessing the impact of noisy activities in cases where the received noise may be greater than the prevailing background noise level, i.e. typically in quiet rural areas.

The open cut coal mining activity in the Hunter Valley is a good example of an environment where these considerations are important. Noise criteria for these mines are often set at an LAeq15-min level of 35dB(A), and the background noise level can be below 25dB(A). In this environment, noise from a mine may meet the criterion whilst being clearly audible, and this can lead to noise complaints. Noise assessments for these mines are conducted in three distinct situations:

- Planning approvals - where typical noise levels that would be acceptable to most people, most of the time need to be defined;
- Complaint investigations - where generally field measurement is conducted and may be supported with modelling assessment;

- Mine noise management - where a combination of monitoring and noise predictions, and forecasts can be used to reactively modify or proactively schedule mining activities for each shift to minimise noise impacts.

The paper focusses on the complaint investigation and mine management aspects and considers the meteorological effects on noise propagation at a specific place and time, as opposed to conducting a general planning assessment of typical, environmental noise levels where existing practices suffice.

2. Meteorological Effects

It is well known that the presence of wind and temperature gradients in the atmosphere will cause soundwaves to deflect, leading to displacement, focussing or dilution of the acoustic energy at any receptor point. This may result in a significant variation in the sound level at the receptor, depending on the specific state of the atmosphere at the time.

Acousticians commonly consider wind and temperature gradients in relatively idealised terms, often assuming a linear temperature or wind profile that is horizontally uniform. In reality this is rarely the case as the actual temperature and wind gradients vary significantly both vertically and horizontally across the spatial domain of interest.

The horizontal variation is generally small in very flat environments but can be significant in hilly terrain where the terrain shape may induce large variations in the wind field and temperature profile. Complex conditions occur during a change in wind direction and it is common to have winds blowing in nearly opposite directions both horizontally and vertically, resulting in steep wind and thermal gradients.

Meteorological conditions tend to be most commonly classified into discrete atmospheric stability classes, such as per the Pasquill Gifford scheme. Not surprisingly, noise and air dispersion models generally adopt such stability classes or idealised extrapolations of vertical and horizontal wind and temperature profiles in making calculations, often on the basis of weather data measured at a 10 metre height.

The actual, complex meteorology several hundred metres above ground level has a significant effect on noise propagation over distances measured in kilometres. Acousticians report noise enhancements of 10dB and up to 20dB under extreme meteorological conditions. A related example is apparent in the margin of error of nominally ± 6dB between the line of best fit and the measured data in the CONCAWE experiment as relevant to this case. Whilst other noise models may adopt different approaches, the author is unaware of any commercial noise model that can consistently make an accurate calculation of the short term noise level at a specific time at a place kilometres from a source. Some of the key factors that make such calculations challenging are considered in this paper.

3. Wind Gradients

Acousticians understand that it is not the wind as such, but rather the change in vertical wind speed with height which affects noise propagation over distance. As the speed of sound is much greater than the actual wind speed, a steady wind with no vertical wind speed gradient would not cause any perceptible effect on the noise level received, either upwind or down wind. However, due to friction, winds near the ground surface tend to be lower and typically the wind speeds will increase with height under most conditions. This can be illustrated in the following picture of a smoke experiment conducted by NASA at its Lewis Research Centre near Sandusky, Ohio using an experimental wind turbine. The image shows that the distance between the smoke trace at the upper part of the blade sweep is approximately 25% greater than in the lower part of the sweep, indicating approximately 25% greater wind speed at height.

Figure 1. Smoke experiment by NASA on an experimental wind turbine

In these conditions, the upper part of a sound front will be acted on by a faster wind speed. Over some distance downwind, this will cause the upper part of the sound front to travel further away from the source than the lower part, which causes the front to curve downwards, potentially increasing the noise level downwind at ground level. The opposite occurs for sound fronts travelling upwind, and the front and hence noise will be directed further upwards with increasing distance from the source, decreasing the noise level upwind at ground level.

The idealised case of a linearly increasing wind gradient is often used to illustrate this phenomena but a better approximation of the "idealised case" would be to assume a wind speed that varies per a power law relationship

$$u = u_x \left(\frac{z}{z_x}\right)^{\alpha} \quad (1)$$

where u is the wind speed at desired height z, u_x is the known wind speed at height z_x, and α is a wind profile exponent. Equation (1) is generally reliable when α can be derived from measurements at two heights. The equation is used to estimate the wind speeds at the heights where wind gradients may play a significant role in noise propagation over kilometres, and where there is relatively clear level terrain free of obstacles, trees etc. More complicated logarithmic relationships can be applied to provide an even better estimate of the wind profile within several tens of metres from the ground but this requires knowledge of terrain and vegetation factors that affect surface roughness. These approaches have been applied in some of the most common air dispersion models for many decades and more advanced and accurate procedures have been in general use in air modelling for over a decade in the US and Australia.

The following figures illustrate the two dimensional effects on sound rays assuming a linear, power law and per an "actual" wind gradient with height above a point on flat ground. (Please note that for clarity, the wind direction is set to a westerly and the vertical scale is exaggerated.)

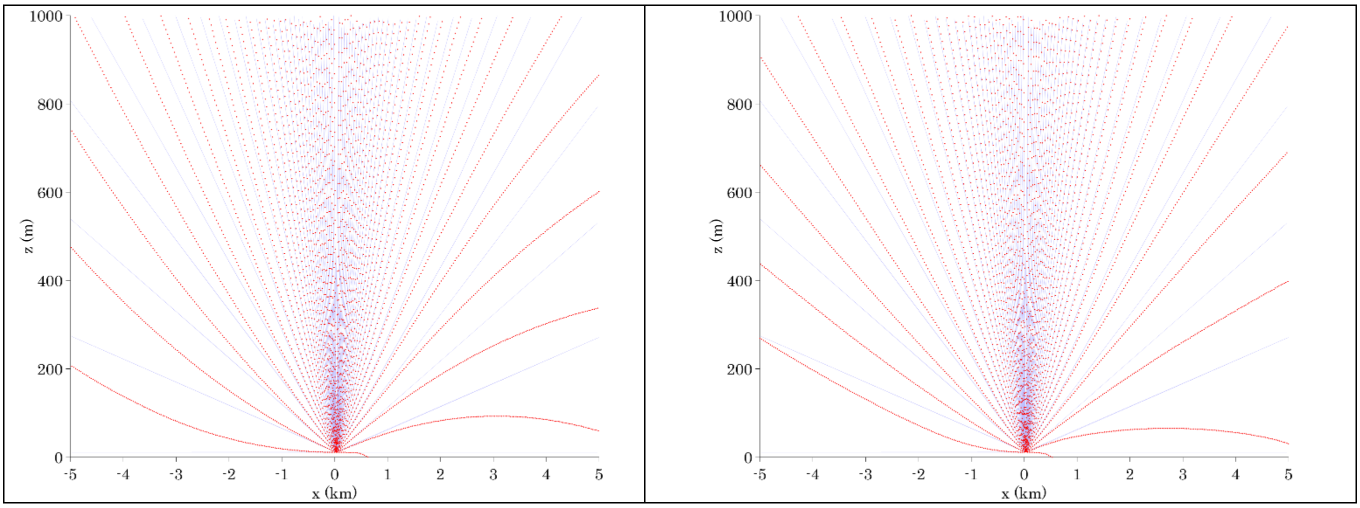

Figure 2. Idealised wind profile (linear on left and power law on right)

The figures show that (upon close inspection) relative to the linear wind profile, the power law profile has a larger effect near ground level but less effect with increasing height and thus it may be expected that noise models using non-linear wind profiles may better predict distant noise levels. Of course in the real world the actual wind profile may be more complicated, as illustrated in Figure 3. Example of "actual" wind profile:

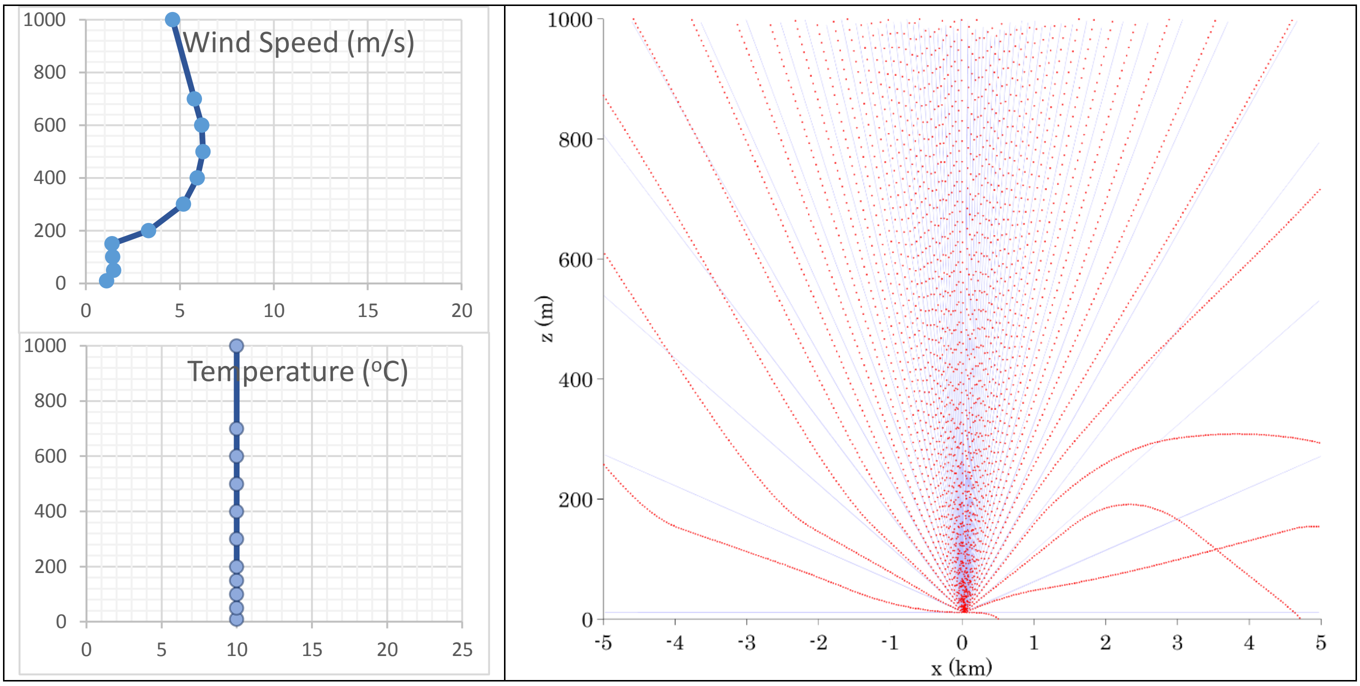

Figure 3. Example of "actual" wind profile

4 Temperature Gradients and Noise Propagation

Temperature gradients act on sound waves in a similar manner to that outlined for wind gradients, except that the deflection of the sound front arises because sound travels faster in warmer air. Thus where there is a temperature inversion, i.e. there is progressively warmer air with increasing height above ground, the upper part of the sound front will travel faster than the lower part, causing the front to curve downwards thus focussing more acoustic energy at ground level (and directing less energy upwards).

Wind gradients may increase downwind noise and reduce upwind noise (i.e. re-distribute acoustic energy in the horizontal). However provided that the thermal gradient is horizontally uniform an inversion will increase the acoustic energy at ground level in all horizontal directions, and reduce it in the upwards (i.e. re-distribute acoustic energy vertically). However like wind fields, in the real world, thermal gradients are rarely vertically linear or horizontally uniform. There are several key phenomena that lead to the formation of temperature inversions, as outlined in what follows.

4.1 Atmospheric temperature gradients

As the earth is warm and space is cold, the "average" temperature of the atmosphere decreases with height above ground level. If the atmosphere is (hypothetically) entirely still, this decrease in temperature with height is referred to as the environmental lapse rate and would be on average approximately 0.65 degrees per 100m in height through the atmosphere. In this situation there is a negative thermal gradient and the sound fronts are directed upwards and result in lower noise levels (relative to a hypothetical still adiabatic case). However when air is rising or falling (the usual state of the atmosphere) this decrease in temperature with height is known as the adiabatic lapse rate and is defined as a dry adiabatic lapse rate or a wet adiabatic lapse rate.

Whether the rate of change in temperature with height follows the dry or wet adiabatic lapse rate will vary depending on the specific heat capacity of the air, how much moisture it is carrying and how quickly it is rising or falling. To better understand this, consider two situations:

1. A parcel of air rises in the atmosphere, as height increases the pressure drops and this will mean the air expands causing the temperature of the parcel of air to decrease. The converse occurs if the parcel of air falls and the temperature increases as pressure increases. This holds true so long as the air remains dry (unsaturated) air and any moisture it contains remains as a gas and is carried along with the parcel of air. This is known as the dry adiabatic lapse rate and is typically 1.0 degree per 100 metres.

2. A parcel of air rises even further in the atmosphere with greater pressure and temperature drops as it further expands. This will continue with the temperature changing at the dry adiabatic lapse rate until the temperature and pressure fall to the point that the relative humidity of the air reaches 100%. At this time the air becomes saturated (moist) air and as height increases, the moisture in the air begins to condense forming droplets releasing heat into the air. (For convenience we assume that the droplets fall out of the air but in reality there is a transition where very fine droplets remain suspended for some time before they fall out). Thus when such saturated air rises, the rate of cooling follows the wet adiabatic lapse rate which is approximately 0.55 degrees per 100m. The converse occurs as this air then falls, except that it has lost some moisture and now increases temperature with decreasing height at the dry adiabatic lapse rate.

The above may also explain why air driven over a tall mountain range may lose moisture, causing rain on the upwind side and a rain shadow on the downwind side. However the important thing to remember is that descending air increases in temperature.

4.2 Temperature inversion types

4.2.1 Radiation inversions

Radiation inversions are very common at ground level in the cooler months of the year in the evening, night time and morning, generally outside of the daytime period when there is strong direct sunlight. This type of inversion begins to form when the sun's shortwave radiation energy that warms the ground ceases near sunset, after which time the ground loses heat by re-radiating long wave energy to the atmosphere and also by conducting heat to the air just touching the ground, which then rises and through convective processes. The loss of energy increases over time after sunset and essentially warms the air near to the ground, forming a radiation inversion at ground level.

Radiation inversions are greatest in the winter time after clear, still days when the sun has been able to warm the ground significantly without the wind stripping the heat from the ground surface. During days like this the air at the ground surface can be tens of degrees warmer than the air a few hundred metres high. These conditions mean that more heat becomes available to re-radiate into the air near the ground after sunset, resulting in a greater inversion gradient near the ground. This is illustrated in Figure 4.

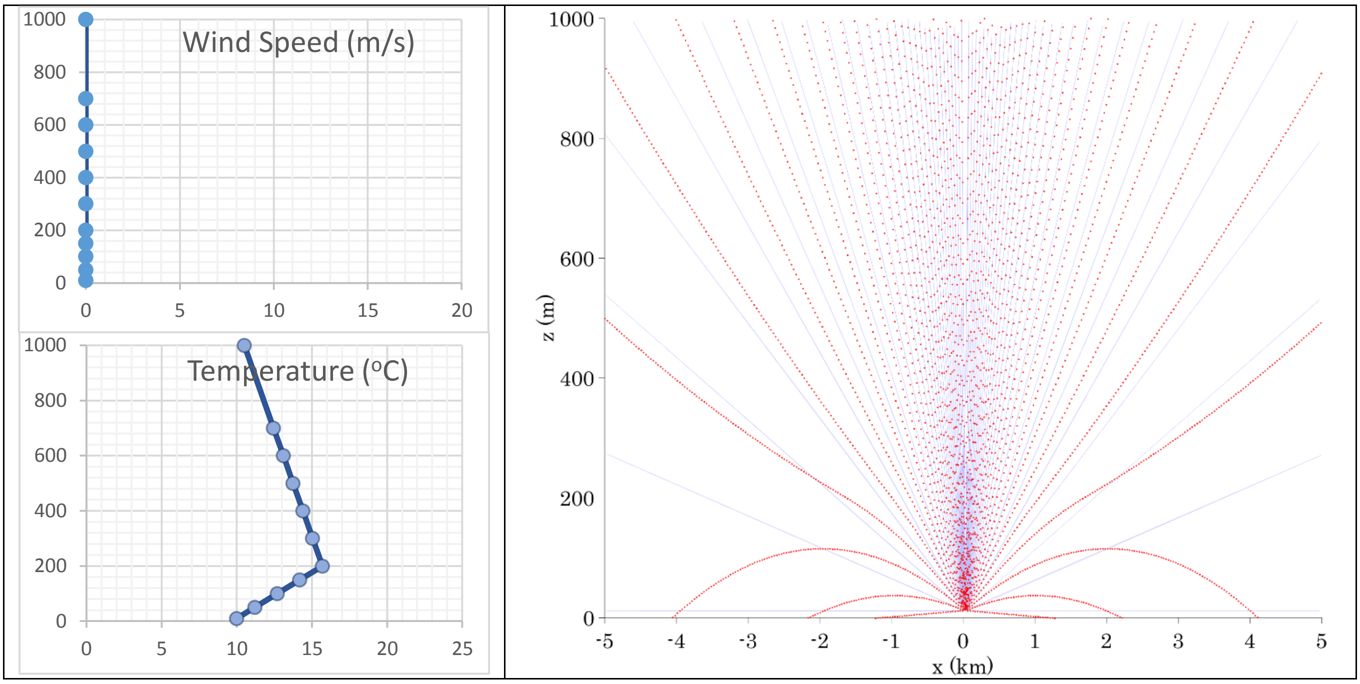

Figure 4. Idealised linear radiation inversion profile

Todoroski Air Sciences has conducted numerous direct measurements which show that in the early part of the night, this type of inversion tends to "hug" the ground and forms a relatively even depth of warm air over the ground, even on relatively steep terrain.

Measurements show that the air can be 8 degrees warmer approximately 30m above ground but that the inversion layer is low (i.e. 30m). The data also show that these inversions tend to increase in height towards the early morning and may exceed 300m in depth with the air approximately 8 to 10 degrees warmer at that height. The inversions are rarely linear however and are generally steepest near ground level.

4.2.2 Subsidence inversions

As outlined in the previous section, descending air increases in temperature. This commonly occurs with high pressure cells that cause the air to slowly sink. This layer of dry air can form a layer, almost always well above ground level, that is very stable i.e. has little air movement to distribute heat and moisture. Sinking dry air caused by high pressure cells or anti-cyclones is a key mechanism leading to the formation of temperature inversions known as subsidence inversions.

On rare occasions a subsidence inversion may come close to ground level, generally when there is a very slow or still high pressure cell and virtually no air movement at ground level. These events are often associated with very poor air quality and include events such as the 1952 London smog, where it is believed that more than 4,000 people died as a direct result of the poor air quality caused by the poor air dispersion conditions. New laws to clean up air quality were enacted but when a similar event occurred in 1962, approximately 750 people died. Such inversions can cover very large areas, essentially the area under the eye of the high pressure cell and may persist for days. Subsidence inversions can be more common in deeper valleys as the inversion can form relatively high in the atmosphere yet still “cap” the valley.

The subsidence inversion causing the great London smog lasted approximately 5 days from 4 to 9 December 1952 and was also accompanied by radiation inversions which formed under the subsidence inversion in the night time. In this case the radiation inversions also persisted during the day (as the winter sun was too low and the fog/ smog too thick for the sun’s heat to warm the ground). This is illustrated in the Figure below.

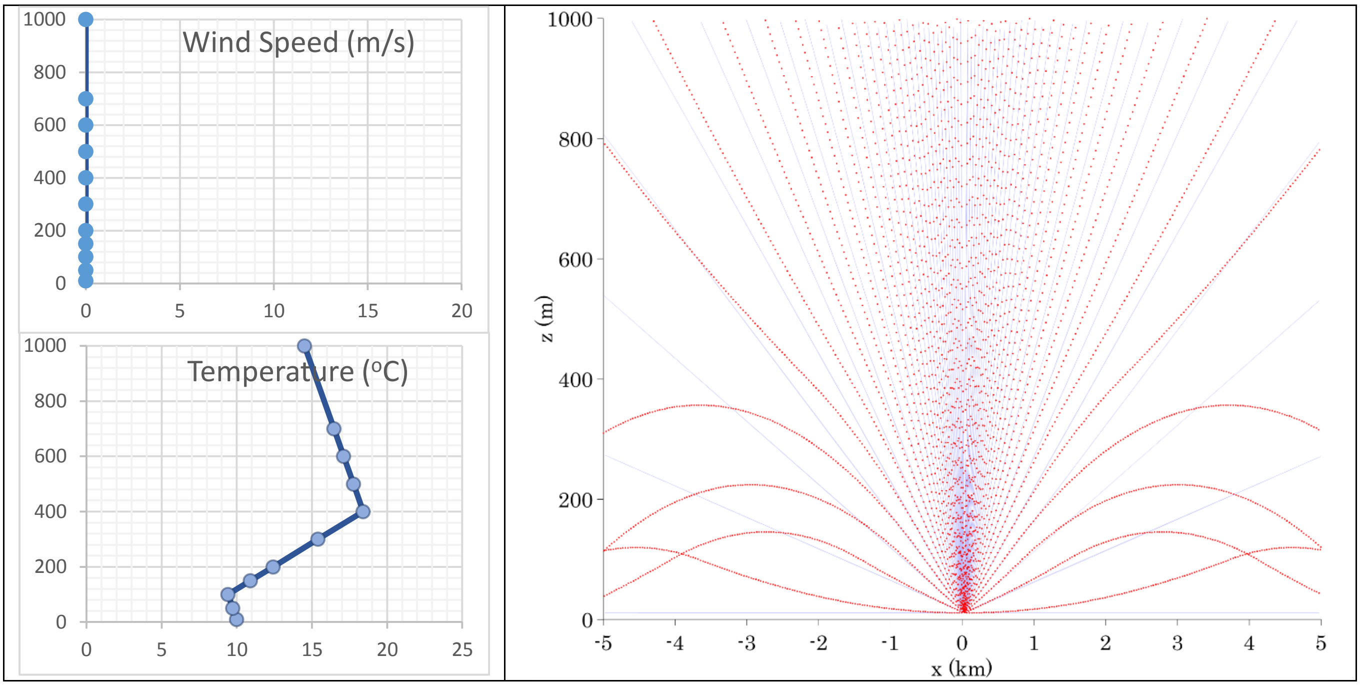

Figure 5. Idealised linear subsidence inversion profile

4.2.3 Frontal and marine inversions

Frontal and marine inversions form when a body of warmer or cooler air associated with a weather front passes through an area. They can occur at any time of the day. These fronts occur a few times a week in the Hunter Valley and are generally associated with a temperature gradient to some degree.

Strong temperature inversions are regularly measured in the winter time and are associated with strong south easterly winds above ground level. This occurs when there is cold often relatively calm air that remains close to the ground whilst the front is passing above. The front generally originates from over the ocean and may be warmer by 12 degrees than the valley air. Eventually the front will stir up the air and dissipate the inversion but the event may last for several hours.

These events cannot be measured using the helium filled balloon favoured by acousticians, (as the winds can reach 10 to 20 m/s and would blow the balloon away) and require specialised equipment such as SODAR (Sonic Detection and Ranging) and RASS (Radio Acoustic Sounding System). This is illustrated in Figure 6. (Please note that for graphing purposes the actual winds are assumed to be westerly only).

4.2.4 Effect of actual inversion and wind conditions

In reality there will almost invariably be a temperature and wind speed gradient present in the vertical and horizontal. The Figure below illustrates the effect of an actual vertical temperature and wind profile with an artificially set westerly wind direction for clarity. These conditions were measured for a frontal inversion in the winter time in the Hunter Valley. The low wind speed winds below 160m were from the west and the higher wind speed winds ranged from the south-east to southerly.

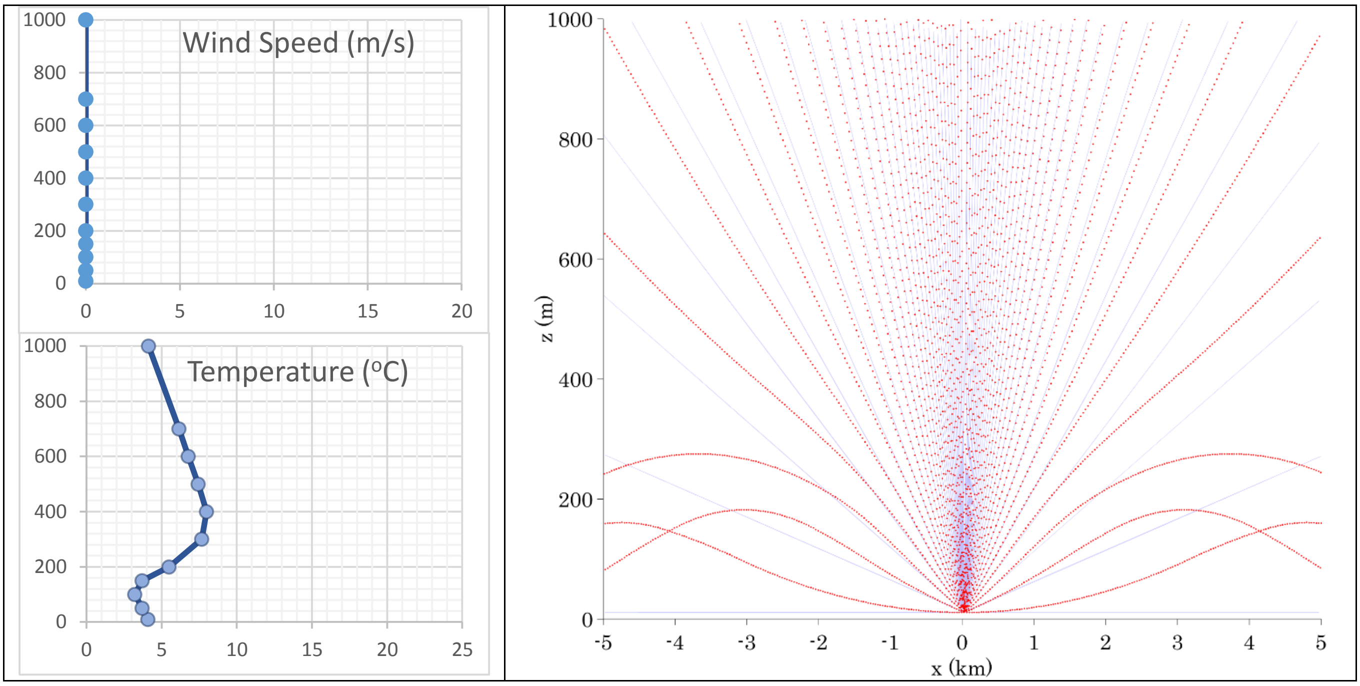

Figure 6. Example of "actual" frontal inversion profile

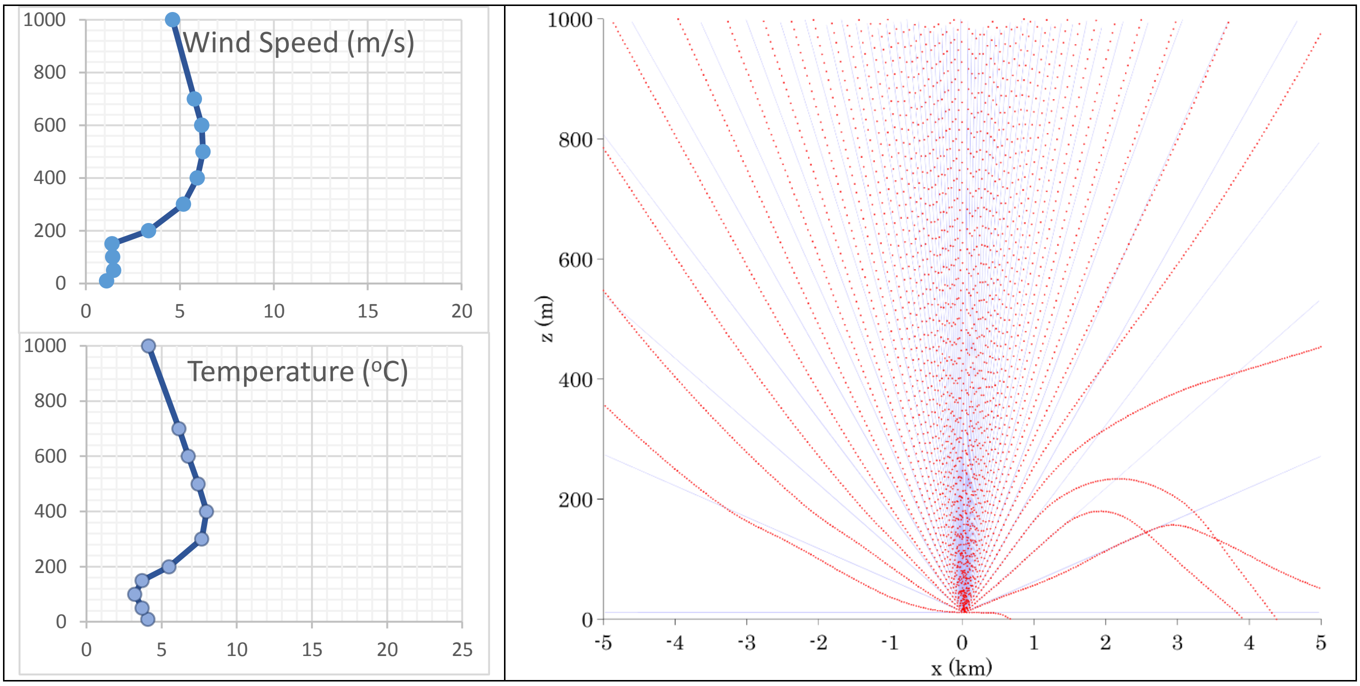

Figure 7. Example of "actual" temperature and wind profile

5. Improving Noise Predictions at a Specific Place and Time

The extent to which any actual wind and temperature gradient may affect noise propagation is challenging to calculate accurately and consistently for short term (i.e. 15-minute) noise impacts. The key challenges arise in establishing a noise model that can accurately and efficiently calculate the noise level for the three dimensionally varying meteorological conditions. Also, as weather conditions change frequently, it may be difficult to obtain accurate temporal data on the spatial variation in the meteorological conditions.

5.1 Meteorological modelling

Standard air quality modelling techniques may involve setting up one or more nested meteorological models to create a two or three dimensional meteorological field for a specific air shed. This field is then input to an air dispersion model that will "release" air pollutants into the meteorological space and track their dispersion as affected by the meteorological conditions. The models provide representative meteorology for each hour of a year, sometimes three or five years, and in some cases each 10 minute period or less. The models can also be run in semi-real time (i.e. several minutes lag time), using a moderately powerful desktop computer. More powerful computers achieve shorter run times and higher spatial and temporal resolutions. To operate, these models typically require data including weather and terrain data (as might be used in a noise model), but also upper air data, that may include synoptic data, forecast data or measured data. Whilst many acousticians have been operating noise models statistically, by covering a range of weather conditions, the approaches tend to compartmentalise the weather conditions and assume uniform horizontal conditions and idealised vertical profiles in the calculations. Noise calculations (for short term far field impacts) appear to be improved by adapting a noise model to accept and take full advantage of the additional time and space varying data available from a meteorological model.

5.1 Mine noise management based on weather and noise forecasts

A modified noise model can incorporate meteorological forecast data in essentially the same way as it would use historical data. There are many numerical metrological forecast models available. The accuracy of the forecasts can be improved by using fine detail terrain data and also processing the data through a series of different meteorological models to take advantage of the strengths of each modelling system in turn. The issue of how to introduce noise sources into the forecasting model can be overcome by considering that even with a large fleet of equipment, it is generally only one or a cluster of plant items that may cause a noise impact off-site. In this context, it would not appear to be critical to model the actual noise level precisely, rather than to represent the increase in noise level due to the meteorological conditions that are forecast. Todoroski Air Sciences have been able to do this successfully, and even a simplified approach (using only one noise source to represent a mine) appears capable of providing reasonably reliable noise forecasts in circumstances where commercial noise models fail. Others, notably Terrock, have developed noise models that have been used with success since the mid 2000's to forecast blast impacts, using a similar approach.

By adopting these methods, the operator can be warned of where and when excessive, additional noise may arise due to meteorological enhancement. This allows pre-shift planning and modifications to activities which may cause impacts in the locations predicted to be affected. An example is provided in the Figure below. More advanced approaches (not shown) identify which plant items are at most risk of causing off-site impacts, allowing the operator to act more precisely, for example by re-locating, slowing, temporarily ceasing etc. specific plant activities.

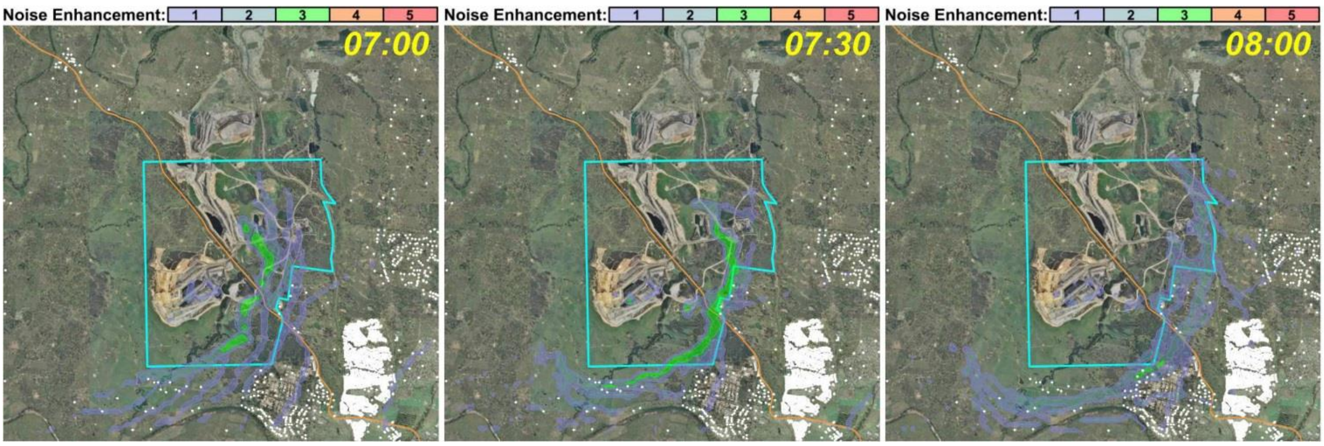

Figure 8. Example of forecast metrological enhancement model output

6. Conclusions

This paper outlines several key meteorological phenomena that can significantly affect noise propagation over distances of kilometres. The figures presented show several idealised cases to illustrate the principles. It is important to note that for clarity the figures showing “actual” cases are adjusted to only show uniform westerly wind directions. In the real world, the situation is more complex than can be illustrated easily in a figure, and this needs to be understood when making noise calculations related to short term impacts over such distances.

Common noise modelling approaches tend to apply empirical best fit equations, or idealised meteorological scenarios. Improvements can be made by modelling many scenarios and statistically considering the results in order to represent typical noise levels that may arise over the course of a year. Thus if this is the aim, there is no apparent need to modify these approaches. However where the objective is to predict short term impacts at a specific place and time, for example to assist with management of noise in a real-time or predictive manner, the standard approaches do not appear reliable.

Accurately calculating noise levels, at short time intervals at a specific time and place kilometres from a source is difficult, but can be achieved by adapting noise models such that they may incorporate standard meteorological modelling and forecasting methods, in order to reliably represent noise enhancement under real-world meteorological conditions. More sophisticated approaches have also been developed but are outside of the scope of this paper. Adapting noise models for this purpose, or otherwise managing operational noise impacts over large distances requires a good understanding of the key mechanisms that lead to noise enhancement, as outlined in this paper.