# Wind and Temperature Effects on Sound Propagation

Lindsay Hannah
Malcolm Hunt Associates, Wellington, lindsay@noise.co.nz

Not Refereed

*The third in a series of articles taken from a paper entitled "Factors Affecting Outdoor Sound Propagation", submitted in part fulfillment of a course at Massey University, 2006*

## Wind

As discussed in the previous article, wind and temperature variations can cause bending of sound waves and can influence changes in sound levels, predominately at large distances. These are normally short-term effects.

The most significant effects that can influence the long range propagation of noise are those introduced by variations in atmospheric conditions – specifically, wind and temperature gradients.

By itself, wind has very limited effects on noise propagation, other than to increase or decrease the speed of sound. At short distances, up to 50m, the wind has minor influence on the measured sound level. For longer distances, the wind effects become appreciably greater.

Over open ground, substantial vertical wind velocity gradients commonly exist due to friction between the moving air and the ground. Wind speed profiles are strongly dependent on the time of day due to the Suns radiation on the Earths surface, weather conditions, and the nature of the surface. The speed of sound waves is relative to that of the medium through which they travel, and hence the relative velocity is a sum of the sound velocity (c) and wind velocity (u) hence c+u or c-u.

A steady, smooth flow of wind, equal at all altitudes, would generally have no noticeable effect on sound transmission.

In real life however, wind speeds are higher above the ground than at ground level, and the resulting wind speed gradients tend to "bend" sound waves over large distances. The wind is also not constant at the same height – it varies from place to place.

Sound travelling with the wind is bent down to earth, while sound travelling against the wind is bent upwards above the ground.

The downwind and upwind effects are summarised below. Irregular, turbulent, or gusty wind provides fluctuations in sound transmission over large distances (this may be because of partial wavelength interference of various paths taken by various sound rays of the total beam).

The net effect of these fluctuations may be an average reduction of a few decibels per 100 yards (90m) for gusty wind with speeds of 15 to 30 mph (20 to 50km/hr).

### Downwind Effects[1]

Wind velocity increases with height and so downwind the combined velocity increases with height and the sound waves are refracted towards the ground, giving an increase in the expected level of sound at a distant point.

This leads to a favourable condition for the propagation of sound and ensures good audibility over larger distances.


**Figure 34: Example of downwind sound diffraction[8].**

The stronger the wind, the more pronounced is this effect (up to a certain wind speed).

Figure 34 illustrates the principle of downwind sound propagation. When there is no wind, the principal sound arrives at the receiver by Path 1. Along this path, the ground, vegetation, and trees can absorb some of the sound.

During downwind conditions, however, the Path (2) sound (that normally travels upward into the sky and does not return to Earth) is bent down and returns to the earth, sometimes passing above the attenuation from ground surface and vegetation, thus yielding higher sound levels at the receiver.

This can occur only for relatively large distances between source and receivers (approx 1000ft (300m) or more).

In summary, downwind can reduce or eliminate some of the attenuating effects of terrain and vegetation or a solid barrier that otherwise would "intercept the sound path".

Downwind measurements are normally preferred by acoustical consultants as the variability is smaller and the result is viewed as conservative and "worst case".

### Upwind Effects

Upwind, the combined velocity decreases with height and the sound waves are refracted away from the Earth's surface. These areas are referred to as shadow zones.

A strong persistent upwind can cast a shadow zone, as shown schematically in Figure 35. When wind speed profiles are known, the distance to the shadow zone can be estimated, but this is an impractical field evaluation.

It is sufficient to realise that the shadow zone can account for sound level reductions up to about 20dB, and that this can occur at distances greater than about 1000 feet (300m) for wind speeds above about 10 to 15 mph (16 to 24 km/hr).

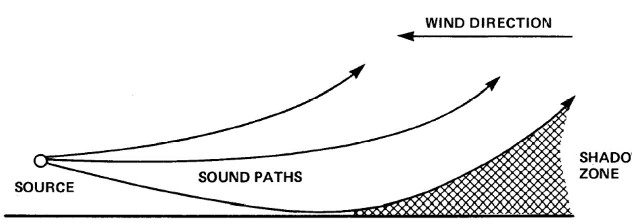


**Figure 35: Example of up-wind sound effects[9].**

Downwind, the level will generally increase; this increase in terms of dB depends upon the changing wind environment, namely the wind speed. When measuring upwind or a side wind, the level can decrease by 20dB or more, depending on wind speed and distance.

Figure 36 illustrates the potential sound level reductions in terms of dBA in relation to down wind, side wind or upwind relative to distance. As illustrated, the potential sound level reductions generally increase for side and upwind directions respectively relative to an increasing distance from the source.

Based on a distance of 1000m from source, Figure 38 yields a downwind reduction of up to 5dB (probably due to distance effects not wind) side wind reductions of up to –11dB and an upwind reduction of up to –20dB.

Figure 36 illustrates that sound levels reduce further from source, with the greatest reductions yielded for upwind measurements.

The CONCAWE noise prediction model indicates that while downwind effects of slight winds (1 to 3 m/sec) provide for positive enhancement (up to 5dB per kilometre), higher wind speeds induce significant scattering and dissipation of sound such that sound levels downwind do not accentuate beyond that found at 5 m/sec.

## Temperature[2]

Earth is a “heat machine” driven by the heating and cooling of the atmosphere that obeys the law of gases. A gas allowed to expand becomes cooler; the same volume of gas compressed into a smaller space becomes warmer.

When the same volume of gas is compressed the molecules are closer together and collide more frequently, raising sensible heat. Such a process, in which heat is neither lost to, nor gained from the “outside environment” is termed an adiabatic process.

The temperature change is called the dry adiabatic temperature change.

This adiabatic process occurs when air rises and sinks in the atmosphere. Atmospheric pressure near the ground is greater than at high altitude and therefore the air is warmer near the ground. If a parcel of air is warmer than its surrounding environment it rises.

When this parcel of hot air rises it moves into an area of lower atmosphere pressure and cools at a rate of approx 10 degrees per km (1 degree per 100m). As the mass of air moves up or down, the moisture it contains condenses as it cools because warm air can hold more moisture than cool air. This rate of cooling is known as the moist adiabatic lapse rate.

Earth is heated by day from solar radiation which is absorbed. As air rises and adiabatic cooling continues, the air temperature approaches dew-point which is the temperature at which the air will be saturated with water.

Thus condensation of moisture in rising turbulent air masses gives unstable air masses seen as developing thunderheads on a hot summer day. If a rising air mass cools at a lapse rate less than 1 degree per 100m, it resists

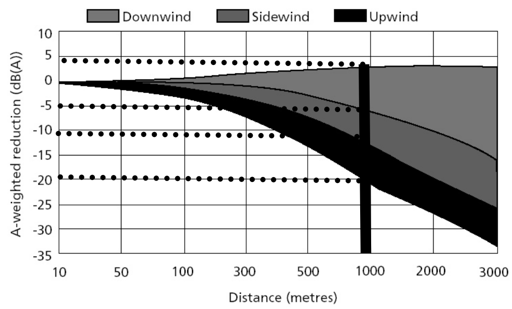


**Figure 36: Potential sound level reductions in terms of dBA relative to a down wind, side wind or upwind situation versus distance traveled from the sound source[10].**

upward movement and may sink lower.

Such air masses are not subject to eddies and turbulence, and when such conditions prevail an air mass is stable, thus cooler air with a temperature lapse rate less than the dry adiabatic rate.

If the lapse rate is the same as dry adiabatic rate then the air mass is neutral, neither resisting nor favouring upward push into the atmosphere.

The behaviour of air masses has a significant influence on climate, from the development of local rain showers in the mountains to massive air movements of a global scale. It also affects the formation of fog and the local concentration and dispersion of pollutants in the atmosphere.

Figure 37 illustrates the adiabatic process for stable and unstable air masses.

## Environmental Lapse Rate (ELR)[3]

Temperature drops an average of 2°C per 300 metres or 7°C per kilometre of height. However, on the basis that an average (or standard constant rate) never really exists in real life, the decrease in temperature with height in more realistic terms should be discussed further.

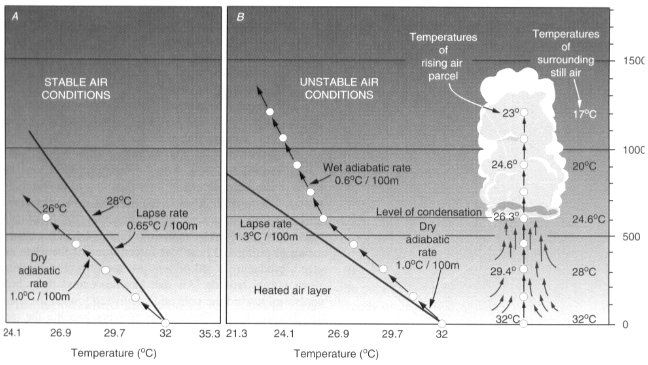


**Figure 37: Adiabatic process for stable and unstable air masses[12].**

The rate at which temperature drops with height at any given time is known as the environmental lapse rate (ELR) of the atmosphere. This rate is constantly changing and readings are obtained at regular intervals every day by ascents into the atmosphere of aircraft or balloons equipped to radio back a variety of data.

The temperature data obtained is crucial, as lapse rates play a major part in the formation of clouds.

There is another type of lapse rate apart from the ELR; it is concerned specifically with air which is forced to ascend within the atmosphere. Such air will cool at a fixed rate, irrespective of the ELR of the atmosphere at the time. This form of cooling is known as adiabatic cooling and at a fixed rate of 3°C per 300 metres it is referred to as the adiabatic lapse rate (ALR).

There will invariably be a difference in the temperature of rising air compared to its environmental atmosphere; this difference has an effect on the rising air.

If at a given time the ELR near the surface is less than the ALR, the ascending air will find itself cooler than the surrounding air; thus, being more dense (heavier) than its surrounds, it cannot continue to rise but will tend to sink towards the surface. In such conditions the atmosphere is said to be stable.

When any rising air attains the same temperature as its environment, it is said to have reached equilibrium.

If the ELR is greater than the ALR, then the ascending air will be warmer than its surround and thus, being less dense (lighter), it will continue to rise. The atmosphere is now considered to be unstable.

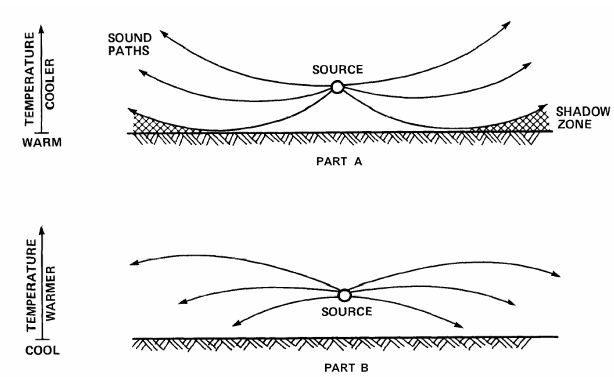


**Figure 38: Effects of temperature gradients on sound propagation. (Top): In the case of upward refraction (temperature decreases with height or upwind propagation) ground based layers are generated into which sound energy is not directly shed. (Bottom): Downward refraction (temperature inversion or downwind propagation) causes multiple reflections at the ground and is known as a condition that is favourable to sound propagation over long distances[11].**

## New Zealand Temperature[4]

Mean temperatures at sea level decrease steadily southward from about 15°C in the far north to about 10°C in the south of the South Island.

Temperatures also drop, by about 2°C per 300m, with altitude. January and February, with approximately the same mean temperature, are generally the warmest months of the year, and July is the coldest. Highest temperatures are recorded east of the main ranges, where they exceed 30°C on a few afternoons in most summers.

The extremes for New Zealand are 42°C. which has been recorded in three places, in the Awatere Valley (Marlborough), Christchurch, and Rangiora (Canterbury); and –22°C at Ophir (Central Otago).

The annual range of mean temperature (the difference between the mean temperature of the warmest and coldest months) is small. In Northland and in western districts of both Islands it is about 8°C and for the remainder of the North Island and east coast districts of the South Island it is 9°C to 10°C.

Further inland the annual range exceeds 11°C in places, reaching a maximum of 14°C in Central Otago where there is an approach to a 'continental' type of climate.

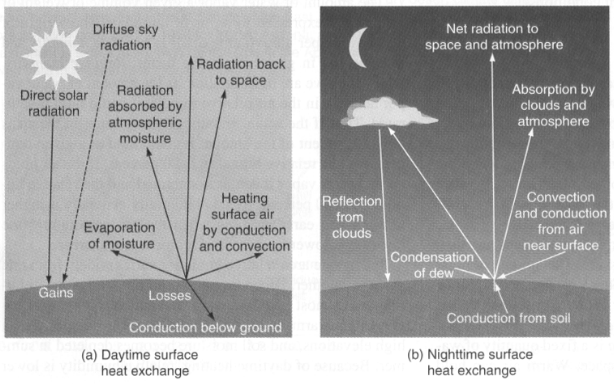


**Figure 39: Radiant heating of the Earth (Left) during daytime heat gains exceed heat loss (Right) at night there is a net cooling of the surface[12].**

The sunniest places are near Blenheim, the Nelson and Motueka area, and Whakatane, where the average duration of bright sunshine exceeds 2350 hours a year. The rest of the Bay of Plenty, and Napier are only slightly less sunny.

A large portion of the country has at least 2000 hours, and even Westland, despite its high rainfall, has 1800 hours. Southland and coastal Otago, where sunshine drops sharply to about 1700 hours a year, lie on the northern fringe of a broad zone of increasing cloudiness.

A pleasant feature of the New Zealand climate is the high proportion of sunshine during the winter months, although there is a marked increase in cloudiness in the North Island in winter but little seasonal change in the South Island, except in Southland.

## Relative Humidity[5]

Moisture is constantly being absorbed into the air from the sea, lakes, rivers and moist ground by the process of evaporation. It exists in an invisible form known as water vapour.

There is a limit to the amount of water vapour that a given mass or 'parcel' of air can contain and the amount actually present at any given time is expressed as a percentage of that limit.

This percentage is known as the relative humidity of the air. For example, if the water vapour content is half the amount of vapour the mass of air can hold, then the relative humidity is 50%.

The effect of temperature on relative humidity is critical. If air is warmed, the relative humidity will decrease as the parcel of air becomes capable of holding a greater amount of water vapour.

The same quantity of vapour becomes a smaller proportion of the total amount that could be contained, thus the relative humidity would decrease.

Conversely, it the temperature drops, the air will be unable to hold as much water vapour and so the existing vapour, which remains the same, will represent a greater proportion of the maximum limit. Should the temperature continue to drop, the relative humidity will increase still further; there can come a time when it reaches 100%.

In relation to New Zealand, mean relative humidity is often between 65 and 85 percent. However, much lower values (from 30 percent down to 5 percent) occur at times in the Southern Alps, where the Foehn Wind (the Canterbury nor-wester) is often very marked. Cool south westerlies are also at times very dry when they reach eastern districts.

In Northland the humid mid-summer conditions are inclined to be oppressive, although temperatures rarely reach 30°C. Dull, humid spells are generally not prolonged anywhere, but their frequency shows a marked increase in the south.

## Temperature Effects[6]

As discussed above, the speed of sound is dependent upon temperature. The Earth receives radiation from the Sun by day and gives out radiation by night (dependent upon the season of the year etc).

Constant temperature with altitude produces no effect on sound transmission, but temperature gradients can produce bending in much the same way as wind gradients do.

Air temperature above the ground is normally cooler than at the ground, and the denser air above tends to bend sound waves upward, as illustrated in Part A of Figure 38. With "temperature inversions," warm air above the surface bends the sound waves down to earth.

Inversion effects are negligible at short distances but they may amount to several dB at very large distances (say,

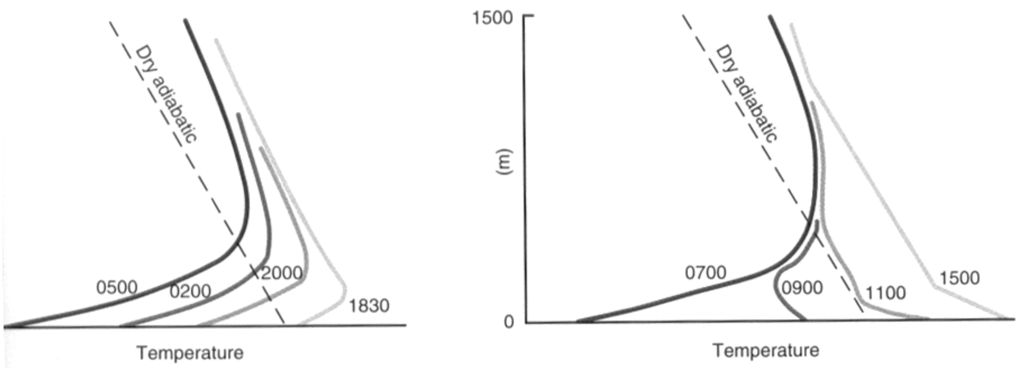


**Figure 40: (Left): As the ground cools rapidly after sunset a surface inversion forms, as cooling continues during the night the inversion deepens from the surface upward reaching its am depth just before dawn around 5.00am. (Right) After sunrise the surface begins to warm and the night surface inversion (0700) is graduated eliminated during the forenoon of a clear summer day[12].**

over a half mile or 0.8kms). Again, little or no increase is caused by thermal gradients (compared to homogeneous air), but there may be a decrease in sound levels.

A temperature increase with height is known as a temperature inversion. This is often the case in clear nights and during fog in winter. But also after heavy rain falls and above snow covers, the temperature often rises with height.

Under these circumstances, sound waves are refracted downward and good audibility is achieved over long distances (refer Part B of Figure 38).

If, however, moderate or strong wind is blowing towards the source of the noise at the same time, the upward refracting effect of temperature increase is over-compensated by the downward refracting effect of downwind propagation. As a consequence an acoustical shadow may form and audibility may be reduced.

The Earths surface heats up by day and by night gradual radiation cools the surface air above as illustrated in Figure 39.

The formation and elimination of a night time surface inversion (typically on a clear cool night) is shown in Figure 40.

Inversions can be prominent in the early morning prior to sun rise when the ground is at its coolest and there is minimal or no wind to cause turbulence and mix the cold surface air with the warmer air above.

Once the sun has been up for a while, the ground warms and the inversion gradually disappears. An inversion acts as a 'trap' for air containing haze, mist and fog.

If initially forced to rise, the air immediately becomes cooler than the warm air aloft surrounding it and sinks back. In other words the atmosphere will be stable at the time of an inversion.

Inversions are particularly pronounced in hilly and mountainous country in summer when the air mass is stable and the weather is calm and clear.

Figure 41 illustrates this concept when at night air in the valley cools next to the ground forming a week surface face inversion.

At the same time, the cold dense air flows down the slopes from the hill or mountain. Together they cause inversions to become deeper and stronger and the cold dense air is trapped beneath a layer or warm air.

Subsidence inversions that bring about concentration of pollution are often accompanied by lower level radiation inversions. Figure 42 illustrates the decent of a subsidence inversion. The movement of the inversion is traced by successive temperature measurements indicated by the dashed lines. The nearly horizontal dashed line indicates the descending base of the inversion, the solid line indicates temperature.

The temperature lapse rate in the descending layer is nearly dry adiabatic. The bottom surface is marked by a temperature inversion. Two features, temperature inversion and a marked decrease in moisture, identify the base of the subsiding layer.

Inversions can last for days, particularly during periods when anticyclones are in place. If you were to fly up through an inversion you would suddenly burst into clear conditions with vastly increased visibility.

The dividing line is quite sharp. Certain meteorological conditions may increase noise levels by focusing sound wave propagation paths at a single point. Such refraction of sound waves occurs during temperature inversions and where there is a wind gradient

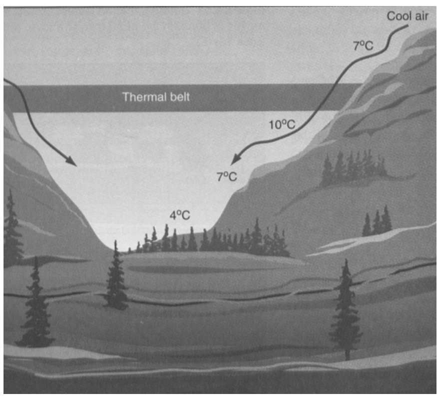


**Figure 41: Topography plays an important part in the formation of night time temperature inversions[12].**

(wind velocities increasing with height) with wind direction from the source to the receiver.

These conditions typically increase noise levels by 5dB to 10dB and have been known to increase levels by as much as 20dB. Temperature inversions occur within the lowest 50m to 100m of the atmosphere, hence can affect noise level measurements on local ground level.

Temperature inversions are most commonly caused by radiative cooling of the ground at night, leading to the cooling of the air in contact with the ground; this is especially prevalent on cloudless nights with little wind.

Air that is somewhat removed from contact with the ground will not cool as much, resulting in warmer air aloft than near the ground.

Under conditions of a temperature inversion, sound waves will be refracted downwards. Therefore they may be heard over larger distances. This frequently occurs in winter and at sunset.

The refraction of sound waves by two layers of air at different temperatures as a result of the change of speed of the sound is illustrated in Figure 43.

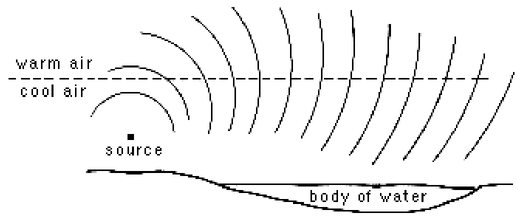


**Figure 43: Refraction of sound waves by two layers of air at different temperatures[13].**

When a wind is blowing there will always be a wind gradient. This is due to the layer of air next to the ground being stationary.

A wind gradient results in sound waves propagating upwind being 'bent' upwards and those propagating downwind being 'bent' downwards.

Temperature and wind gradients can result in measured sound levels being very different to those predicted from geometrical spreading and atmospheric absorption considerations alone. These differences may be as great as 20dB, and are particularly important where sound is propagating over distances greater than a few hundred metres.

Temperature inversions and winds can also result in the effectiveness of a barrier being dramatically reduced[104].

A common atmospheric occurrence is a negative temperature gradient (temperature decreases with altitude). This is typical of a sunny afternoon, when significant solar isolation causes high surface temperatures and significant heat transfer from the ground to the adjacent air.

This event is also known in meteorological terms as a superadiabatic or positive lapse.

In this situation, sound waves will be bent upward in all directions from the source, forming a circular shadow zone. The reverse situation often occurs at night, when a positive gradient is common. This is caused by the rapid cooling of air at the surface as heat is now absorbed by the ground. This is called an inversion or negative lapse and the sound waves are bent downward.

This phenomena explains why sound sometimes travels much better at night, because it is focused along the ground instead of radiating upward. For completeness of meteorological terminology, a neutral (or statically stable) atmosphere is defined as one in which the temperature decreases at the dry adiabatic rate (–9.8°C/100 meters).

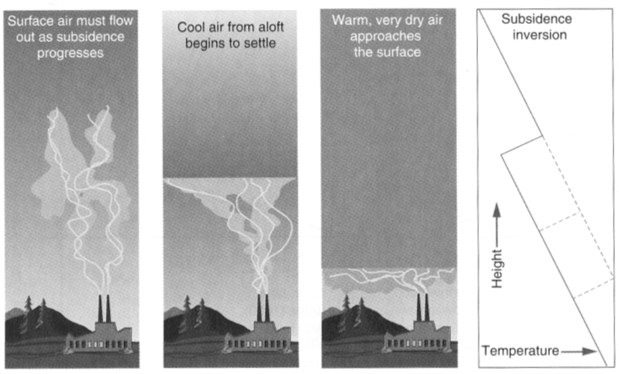


**Figure 42: Decent of a subsidence inversion[12].**

In a neutral atmosphere, buoyant effects are balanced by gravity and there is no upward or downward convection. This is not the same as a non-refractive medium. In order to attain straight sound paths (no refraction), the atmosphere must have a constant temperature (isothermal).

Temperature gradients greater than –9.8°C/100m are called positive lapse or superadiabatic, while gradients less than this value are called negative lapse or inversion. Refraction of sound with temperature gradients is shown in Figure 44.

It is extremely important to understand refraction in order to make reliable sound measurements at large distances from a source.

An unscrupulous consultant may take advantage of refraction to make measurements which are the most favourable. For example if you wanted the observed levels to be low, measure on a hot sunny afternoon, or upwind from the source. If you wanted levels that are more representative of the equivalent sound level, measure when the refractive effects are at a minimum – on a calm, overcast day or evening.

Nevertheless, the conditions should always be recorded and the appropriate standards used stated, so other consultants may review and reproduce others work.

## Atmospheric Absorption

Knowledge of the rate at which acoustic energy is absorbed during propagation through the atmosphere comes from three sources being:

1. Direct measurements in the field;
2. Measurements of air absorption in the laboratory;
3. General knowledge of the physical and mechanical mechanisms;

## Molecular Absorption[7]

Air absorbs sound energy. As a sound

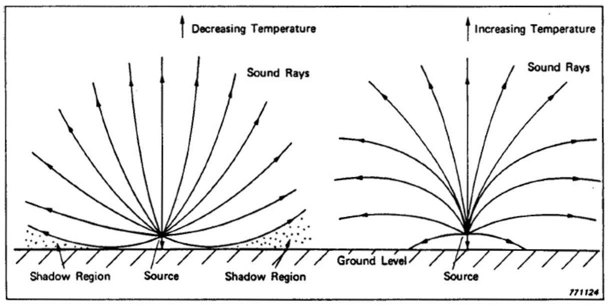


**Figure 44: Refraction of sound with temperature gradients (Left): Normal lapse rate (decreasing temperature with altitude) (Right): Inverted lapse rate temperature increases with altitude)[13].**

wave travels through the air, a small proportion is absorbed by the air itself. The absorbed sound energy is converted to heat.

The amount of absorption is dependent on the temperature and humidity of the air and the frequency of the sound. As the sound waves propagate through the air, sound energy is lost due to friction between air molecules and because of further properties of the molecules themselves.

The main mechanism is the setting up of vibrations in the molecules of oxygen and nitrogen in the air. High frequencies are much more affected by atmospheric absorption than low frequencies.

Over small distances (up to a few hundred metres) atmospheric absorption can generally be ignored, as its effect is minor compared with that of spherical spreading. Conversely, in long distance propagation (e.g. aircraft noise) the absorption effect is not ignored.

The effect is clearer over longer distances and is frequency dependent, with the higher frequencies being attenuated far more than lower frequencies. It depends on temperature and relative humidity. A "standard day" may be, and is frequently defined, as having a temperature of 20°C and a relative humidity of 70%.

ISO9613-2 defines the attenuation due to atmospheric absorption, referred to as $A_{amt}$ (dB), during propagation through distances d (m) as:

$$A_{amt} = \alpha d/1000$$

where α is the atmospheric attenuation coefficient (dB) per kilometre for each octave band at the mid band frequency.

The atmospheric attenuation coefficient (α) can be determined from Figure 45, as reproduced from ISO Standard 9613-2 (Table 2).

Figure 46 illustrates the attenuation due to absorption for a "standard day".

As can be seen in figures 45 and 46, the atmospheric attenuation coefficient depends strongly on the frequency of the sound, the ambient temperature, and the relative humidity of the air. It is common for a value of 0.005dB/m to be used (at 1000Hz).

A small part of a sound wave is lost to the air or other media through various physical processes. One important process is the direct conduction of vibration into air as heat, caused by the

**Table 2 — Atmospheric attenuation coefficient α for octave bands of noise**

| Temperature | Relative humidity | Atmospheric attenuation coefficient α, dB/km | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Nominal midband frequency, Hz | | | | | | | |
| °C | % | 63 | 125 | 250 | 500 | 1 000 | 2 000 | 4 000 | 8 000 |
| 10 | 70 | 0,1 | 0,4 | 1,0 | 1,9 | 3,7 | 9,7 | 32,8 | 117 |
| 20 | 70 | 0,1 | 0,3 | 1,1 | 2,8 | 5,0 | 9,0 | 22,9 | 76,6 |
| 30 | 70 | 0,1 | 0,3 | 1,0 | 3,1 | 7,4 | 12,7 | 23,1 | 59,3 |
| 15 | 20 | 0,3 | 0,6 | 1,2 | 2,7 | 8,2 | 28,2 | 88,8 | 202 |
| 15 | 50 | 0,1 | 0,5 | 1,2 | 2,2 | 4,2 | 10,8 | 36,2 | 129 |
| 15 | 80 | 0,1 | 0,3 | 1,1 | 2,4 | 4,1 | 8,3 | 23,7 | 82,8 |

**Figure 45: Table 2 of ISO Standard 9613-2 *Acoustics Attenuation of Sound during Propagation Outdoors* atmospheric attenuation coefficient, dB/km (α).**

| Attenuation by air absorption at 20 °C and 70 % relative humidity. (ISO 9613-2) | |
|---|---|
| 63Hz | 0.1dB/km |
| 125 Hz | 0.3 dB/km |
| 250 Hz | 1.1 dB/km |
| 500 Hz | 2.8 dB/km |
| 1000 Hz | 5.0 dB/km |
| 2000 Hz | 9.0 dB/km |
| 8000 Hz | 76.6 dB/km |

**Figure 46: Atmospheric attenuation coefficients, dB/km (α) for a "standard day".**

conversion of coherent molecular motion of the sound wave into incoherent molecular motion in the air or other absorptive material.

The viscosity (thickness) of the medium also affects sound transmission. These two physical causes combine to produce the classical attenuation of a sound wave.

Atmospheric absorption increases linearly with distance. Very little attenuation is found for low values of relative humidity or temperature.

Monthly and diurnal variations in relative humidity and temperature introduce large variations in atmospheric absorption. Usually, relative humidity reaches its maximum soon after sunrise and its minimum in the afternoon when temperature is highest. The diurnal variations are greatest during the summer.

Figure 47 shows an absorption value 0.25 dB/100 m for 30% relative humidity and 20°C for the middle speech frequency range (2kHz).

It should be noted, however, that absorption can be as high as 5.0dB/100 m at 8kHz when the temperature is 20°C and the humidity is 10% (see Figure 47, right hand graph).

Under 'normal' circumstances, atmospheric absorption can be neglected, except where long distances or very high frequencies are involved.

## References

The above article has been complied from previous research carried out by other authors, and anything referenced in this paper has been directly reproduced from the original authors work as referenced below.


**[1] Wind**

United States Air Force, Noise and Vibration Control, A Technical Air Force Manual No.88-3., 1995.

Cosgrove, B. 1997. The World of Weather. Swan Hill Press.

CONCAWE report 4/81 The Propagation of Noise from Petroleum and Petrochemical Complexes to Neighbouring Communities.

Renzo Tonin. Modelling and Predicting Environmental Noise. Renzo Tonin & Associates Pty Ltd Pty Ltd, 1/418A Elizabeth St., Surry Hills NSW 2010, Australia.

**[2] Temperature**

Bruel and Kjaer. Environmental Noise Handbook.

Smith, Leo Robert. Ecology and Field Biology (Fifth Edition). Harper Collins College Publishers. 1996

United States Air Force, Noise and Vibration Control, A Technical Air Force Manual No.88-3., 1995.

**[3] ELR**

Smith, Leo Robert. Ecology and Field Biology (Fifth Edition). Harper Collins College Publishers. 1996

Cosgrove, B. 1997. The World of Weather. Swan Hill Press.

**[4] NZ Weather**

Overview of Meteorological Service on New Zealand. Publication No 15.

**[5] Relative Humidity**

Cosgrove, B. 1997. The World of Weather. Swan Hill Press.

Smith, Leo Robert. Ecology and Field Biology (Fifth Edition). Harper Collins College Publishers. 1996

Overview of Meteorological Service on New Zealand. Publication No 15.

**[6] Temperature**

Dr. Dietrich Heimann of Institut für Physik der Atmosphäre.

Smith, Leo Robert. Ecology and Field Biology (Fifth Edition). Harper Collins College Publishers. 1996

New South Wales Industrial Noise Policy.

Ingard, A Review of the Influence of Meteorological Conditions on Sound Propagation, Journal of the Acoustical Society of America, 25, p. 405.

**[7] Molecular Absorption**

Cyril Harris, Absorption of Sound in Air versus Humidity and Temperature, Journal of the Acoustical Society of America, 40, p. 148.

**Figures**

[8] Figure 34. United States Air Force, Noise and Vibration Control, A Technical Air Force Manual No.88-3., 1995.


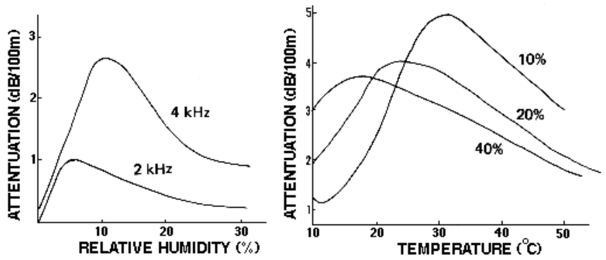


**Figure 47: (left): Frequency dependence of attenuation as a function of relative humidity at 20°C. (Right): Attenuation as a function of temperature for various percentages of relative humidity[7].**


[9] Figure 35. Cosgrove, B. 1997. The World of Weather. Swan Hill Press.

[10] Figure 36. Bruel and Kjaer. Environmental Noise Handbook.

[11] Figure 38. United States Air Force, Noise and Vibration Control, A Technical Air Force Manual No.88-3., 1995

[12] Figure 37, 39, 40, 41, 42. Smith, Leo Robert. Ecology and Field Biology (Fifth Edition). Harper Collins College Publishers. 1996

[13] Figure 43, 44. Malcolm Hunt Associates. ❑