OCEAN AMBIENT NOISE: ITS MEASUREMENT AND ITS SIGNIFICANCE TO MARINE ANIMALS

Douglas H. Cato Defence Science and Technology Organisation, and University of Sydney Institute of Marine Science, Sydney, NSW 2006 Australia.

1 INTRODUCTION

Ambient noise in the ocean is generally considered to be the noise from all sources excluding those that are close enough to be detected individually (on an omni-directional hydrophone). For example, the general background noise from shipping is considered to be part of the ambient noise, but not the noise of an individual passing ship. Sounds of an individual whale close by might also be considered to be not part of the ambient noise, though if many animals are calling to the extent that their calls provide an almost continuous background noise, that might be considered to be ambient noise.

Ambient noise is a basic limitation on the use of sound in the ocean, since sounds of interest must be detected against the ambient noise. It is part of the sound environment that marine animals have to deal with in their use of sound and so an understanding of ambient noise and its range of variation provides a context for assessing the effects of anthropogenic noise. Natural ambient noise varies typically by 20 dB or so over relatively short time scales and variations of 30 dB occur. This variation effects the distance over which animals can communicate; a 20 dB variation in level might typically cause communication ranges to vary by a factor of ten. Marine animals have evolved in this environment so that it is reasonable to assume that they cope adequately with noise levels typical of the range of natural ambient noise and with such large variations in the distances over which their use of sound is effective. There is now, however, a significant component of ambient noise that is anthropogenic and there is interest in determining how this anthropogenic component affects marine animals. For example, a review of ocean noise and marine mammals by the National Research Council of the USA recommended long term monitoring and modelling both ambient noise and noise from identifiable sources, and the effect on marine mammals [1].

2 CHARACTERISTICS, MEASUREMENT AND ANALYSIS OF AMBIENT NOISE.

2.1 CHARACTERISTICS OF AMBIENT NOISE

Ambient noise is complex. It is the combination of contributions of many different sources each differing in behaviour and temporal and spatial dependence. Although there are many sources, the ambient noise itself can be expressed in terms of relatively small number of components, each produced by the contributions of a particular type of source. The most effective way of characterising, predicting or forecasting the noise is to characterise the behaviour of the individual components, each showing temporal and spatial variation related to behaviour of the sources. Early studies of ambient noise [2, 3] established the main components of ambient noise as (a) *sea surface noise*: the noise of wind and wave action at the surface, usually referred to as *wind-dependent noise*, and rain noise; (b) *biological noise*, the noise of fish, whales and invertebrates; and (c) *traffic noise*, the noise of distant shipping. These may be considered to the prevailing components, i.e. the ones that are usually present, though there may be times or locations where one or other are insignificant.

Wind dependent noise is the noise of breaking waves but noise levels correlate better with wind speed than with any measure of wave height or sea state. For example, Perrone [4] cross correlated ambient noise with wind speed and wave height and found that the noise lagged the wind speed by less than 1 h, while wave height lagged wind speed and noise by up to 6 h. Wind-dependent noise results from the oscillation of bubbles formed by air entrainment as waves break [5, 6], and this appears to be more dependent on the forcing by the wind than on the characteristics of the wave height. The dependence of noise on wind speed is very convenient, since it provides a simple way of predicting and forecasting the noise from weather forecasts, and if wind speed is measured together with measurements of ambient noise, this component can be separated from other components.

Traffic noise is the background rumble from the many ships in an ocean basin and does not include contributions from ships close enough to be identified individually [3]. Ships at long distances can contribute to traffic noise if the propagation of sound is good, and many ships in an ocean basin produce high traffic noise levels. This is the main source of anthropogenic ambient noise.

Wind dependent noise extends over a very wide frequency band, from a few hertz to in excess of 30 kHz. In areas of high shipping densities, such as around North America and Europe, traffic noise levels are high and are usually the dominant component at frequencies below about 200 Hz. Most studies of noise have been in these areas, and thus most noise prediction curves do not show wind dependent noise spectra for frequencies below about 200 Hz. However, even in studies in high traffic noise areas there is evidence of high wind dependent noise at low frequencies [e.g. 3, 7]. In waters around Australia, shipping densities vary substantially with the consequence that traffic noise also varies substantially from one region to another [8], and in some areas there are so few ships that traffic noise is negligible. This has allowed reliable measurement of wind dependent noise at frequencies below 200 Hz [8, 9], and it is evident that during high winds (say 30 knots or so), wind dependent noise levels reach levels comparable to traffic noise levels in high shipping areas. Much of the world's oceans would have relatively low levels of traffic noise compared to the areas of the northern hemisphere where most ambient noise measurements have been made.

Biological noise forms a major component of ambient noise but its contribution has often been underestimated. More than one component biological noise may be evident. Biological choruses that result when large numbers of animals (usually conspecifics) are calling commonly increase noise levels by 20 dB or more over typical background noise at low wind speeds and may extend over significant areas [2, 10, 11, 12, 13]. Choruses from fish and invertebrates are common and sometimes choruses are produced by whales [14].

2.2 MEASUREMENT OF AMBIENT NOISE

Measurement of ambient noise requires some care to ensure that the data do not include contributions from system noise, nearby sources or pressure fluctuations induced by turbulence in water flow around the hydrophone and supporting cable. It is generally not possible to measure ambient noise reliably with a hydrophone suspended from a vessel, even if the vessel engines are stopped. The auxiliary machinery on a ship makes significant noise, and noise generated by movement, especially mechanical impact within the vessel will also be recorded. Even from a small boat, the sounds of waves breaking against the hull will significantly contaminate the ambient noise recording. Hence ambient noise is usually measured using buoyed drifting systems or moored systems. Great care needs to be taken in the design of these systems to avoid contamination from the recording system and its moorings or local pressure fluctuations from turbulence due to interaction of the water flow with the measuring system. Noise that is very short in duration or covers a very narrow frequency band can be removed in the analysis if it recognised as contamination. Otherwise it is not possible to remove the influence of contamination. Indeed, it is often the case that contamination cannot readily be detected even when it is present. There are a number of measures that can be taken to minimise contamination.

Noise from turbulence is most significant at low frequencies, the noise spectrum typically decreasing with frequency. Any flow relative to the hydrophone or cable can induce significant pressure fluctuations that will be sensed by a pressure sensitive hydrophone. These are not acoustic pressure fluctuations since they do not propagate and are only locally significant but their magnitude can substantially exceed those of the pressure fluctuations in acoustic noise. In particular, pressure spectrum levels from vortex shedding can be tens of decibels above the ambient noise at their peak frequencies. Vortex shedding occurs as a result of fluid flow across the cross section of an immersed body, such as a hydrophone or a cable. A vortex is shed first on one side and then the other as the flow moves past the body. This causes an alternating pressure fluctuation on the body at a rate equal to the rate of vortex production. This rate or frequency is

$$f_v = 0.2U / d \tag{1}$$

where U is the flow speed and d is the cross section width or diameter. Typically, f_v varies from less than 1 Hz to tens of Hz for usual hydrophone/cable systems and typical flow speeds. Underwater cable can strum across a length such that the natural frequency of this length matches the vortex frequency. This results in very large signals which may overload the hydrophone preamplifier. The effect on a cable suspended from a vessel can usually be felt as vibrations in the cable. There is a tendency for the noise to occur in bursts. Usually, flow noise is limited to frequencies below 100 Hz, so that if the interest is in higher frequencies, the flow noise can be filtered out. Whether or not low frequencies are of interest, it is desirable to place a high pass filter between the hydrophone and its preamplifier so that the turbulent pressure signals do not overload the preamplifier.

The best solution, of course, is to avoid situations were there is likely to be water movement relative to the hydrophone and cable. An effective approach is to place the system on the bottom where water flow is likely to be less than higher in the water column, though even there, vortex shedding can occur. Another approach is to use a drifting system with minimal windage, so the hydrophone and cable move with the water mass. An example is a sonobuoy designed for ambient noise measurement. Such systems are usually suspended from a buoy so the surface motion of the buoy must be isolated from the hydrophone and its cable. For example, if the suspension system has a resonant frequency significantly less than the frequencies of forcing the motion of the buoy (e.g. surface waves), the transmission of the motion to the hydrophone will be minimised.

There are mechanical methods of reducing the pressure fluctuations in the flow past the cable, such as the use of fairings attached to cables of towed arrays. A simple method that I have found to be very effective is to wrap string or cord around the cable near the hydrophone in a helical fashion, with a full cycle being a few centimetres and taped to the cable at sufficient intervals to keep the string in place.

Mechanical noise in any part of the recording system or the mooring can contaminate the recording. Movement or impact of one part against another produces noise and impulsive sounds are commonly picked up in recordings where the system has not been treated to minimise this effect. Any opportunity for parts of the mooring system to impact against each other will cause noise which may be audible for hundreds of metres, and metal parts are the worst. For example, avoid metal coming into contact with metal such as with shackles etc. Chains are best avoided. A fixed ambient noise recording system with the hydrophone on the bottom avoids much of the flow noise, since flow speeds decrease as the bottom is approached across the boundary layer. If currents are high, however, the turbulence may result in significant flow close enough to the bottom to interact with components of the recording system. Cables linking hydrophone and recording package or mooring lines can be affected and it is desirable to ensure that these lie flat on the bottom. A hydrophone linked by cable to shore is a very effective method of measuring ambient noise, but the expense and engineering effort required to lay the cable is substantial and beyond the resources of most research projects. Autonomous systems that can be deployed to record ambient noise are much cheaper and more flexible and the substantial capacity of digital storage now allows long term recordings.

A system that we have used, which includes an anemometer on a buoy to provide the wind speed data, is shown diagrammatically in Figure 1. All moving joints in the mooring section at the hydrophone end are plastic rather than metal and there is no chain or metal anchor at this end. All joints and any other components where there are opportunities for impact are heavily taped to cushion the impact. This taping often has to be reapplied each time the system is re-deployed. At the anemometer end, the requirements are less stringent but it is still necessary to minimise contact noise. Our experience is that flow noise is usually not a problem with the hydrophone on the bottom, but can be significant at times with the hydrophone suspended in the water column. Hence it is better to use a bottom mounted hydrophone, with the upper hydrophone used only where the depth dependence of ambient noise is of interest.

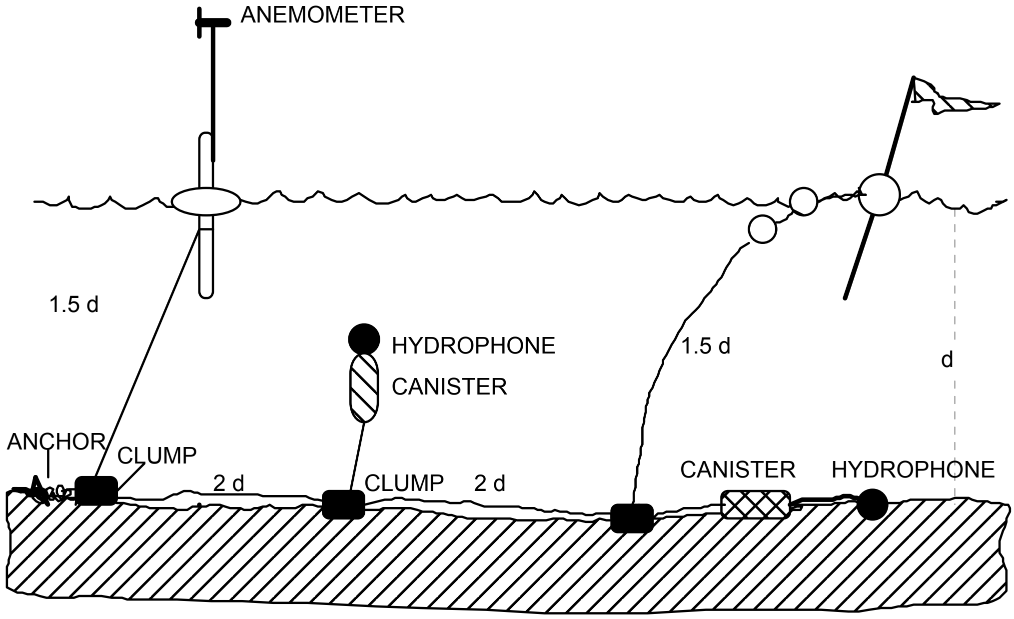

Figure 1: Ambient noise and wind recording system with hydrophone on the bottom and one buoyed up from the bottom. This is not to scale: anchors and line to hydrophone and canister should be far enough apart to ensure that the lines cannot tangle. Nominal line lengths in terms of the water depth *d* are shown.

2.3 ANALYSIS AND INTERPRETATION OF AMBIENT NOISE

Separation of ambient noise into components is an effective way of characterising the noise and leads to methods of prediction and forecast. For example, the correlation with wind speed of noise from breaking waves allows the noise to be forecast from weather forecasts. A biological chorus that shows regular daily patterns can be predicted from the time of day. This is somewhat analogous to forecasting the weather whereas a statistical analysis of ambient noise data (means, variance, percentile values etc) might be analogous to climate statistics, and though useful for some purposes does not provide what is needed for forecasts. Even to obtain a statistical description of the noise, it is far more effective to achieve this by first determining the statistics of the components, since it should significantly reduce the amount of data required to obtain representative values. A spot measurement of ambient noise is of little value since it could lie anywhere within the 20 dB or so variation typically observed for ambient noise. This is analogous to making a spot measurement, say, of rainfall. It tells you whether it is raining or not at the time but tells you nothing about the statistics of the rainfall at that location.

If the purpose of the measurements is to characterise the ambient noise at a particular location, the measurements require an experimental design that allows that noise components to be separated in analysis and their dependence on environmental variables to be determined. Since sea surface (wind-dependent) noise is a ubiquitous component, the first step would usually be to separate wind-dependent noise from non wind-dependent noise.

2.3.1 WIND-DEPENDENT NOISE.

Determination of the wind-dependent noise component is achieved by correlating noise against wind speed. Piggott [7] obtained a relationship between *NL* noise level (in decibels) and the logarithm of the wind speed of the form

$$NL = A + 10n \log_{10} u \tag{2}$$

where A and n are variables that may vary with frequency and the location of measurements, and u is wind speed. This is equivalent to a relationship in which mean square pressure is proportional to wind speed to the power n. Measurement of reliable values of A and n requires measurement of wind speed near enough to the position of the hydrophone for the measured wind speed to be representative of that over the sea surface above the hydrophone. The most effective way is to measure wind speed from a nearby buoy (as in Figure 1 for example), taking care that the buoy does not contribute to the noise.

Wind-dependent noise received at a hydrophone results from sources spread over a significant area of the sea surface, so some spatial averaging of wind gusts occurs, and this is representative of temporal averaging of wind speed for the time it takes for the wind field to move across the area of sources by advection. Frequency analysis of wind gusts [15] gives an idea of the temporal scale of gusts and from this it may be inferred that spatial averaging inherent in the noise measurement will be sufficient to provide a reasonable averaging of gusting [16]. Hence, the position of the anemometer relative to the hydrophone is not critical, although one might expect the correlation of noise with wind speed to decrease as their separation increases. This is, in fact, what has been observed. For example, measurements of noise off Perth, Australia when correlated with wind speed measured by an anemometer on Rottnest Is., 22 km away, gave a similar regression line to that obtained when the noise was correlated with wind speed measured with an anemometer on a buoy 120 m away, though with a greater spread of data [9]. Noise measurements 55 km from Rottnest Is. in deeper water showed a poorer correlation and different regression line (Figure 2). Land based anemometers near shore may be useful in measuring wind when the direction is from the ocean, but may not be representative of wind conditions at sea for winds from land, especially if the anemometer is not well clear of surrounding objects such as buildings or trees. The anemometer on Rottnest Is. has little land surrounding it, so provides measurements representative of those at sea. It is possible to predict wind-dependent noise using wind speeds determined from surface pressure contours in weather maps, though tests show significantly more spread in correlations, as might be expected [9].

The main difficulty in obtaining a representative regression line for dependence of noise on wind speed is the difficulty in separating the wind-dependent and non wind-dependent data. Generally, wind-dependent noise will dominate at higher wind speeds, whereas at low wind speed, the noise will be a combination of wind-dependent noise and noise from other sources. Hence for a particular wind speed, noise will often be higher at low wind speeds than the levels of wind-dependent noise alone. Consequently, a regression line of noise level on the logarithm of the wind speed will have a lesser slope than it would for purely wind dependent noise data. Unfortunately, non-wind-dependent noise is rarely steady enough in level to allow its presence to be apparent in any individual measurement so that it is usually not clear how it contributes to each data point. Slopes vary depending on the contribution of non-wind-dependent noise. In the example in Figure 2, there is significant contribution from non-wind-dependent noise sources at lower winds speeds, which tends to flatten the regression line, giving $n \approx 1.7$. In measurements at locations where there is little contribution from non-wind-dependent noise, n is close to 3 for this frequency (see example in reference 16).

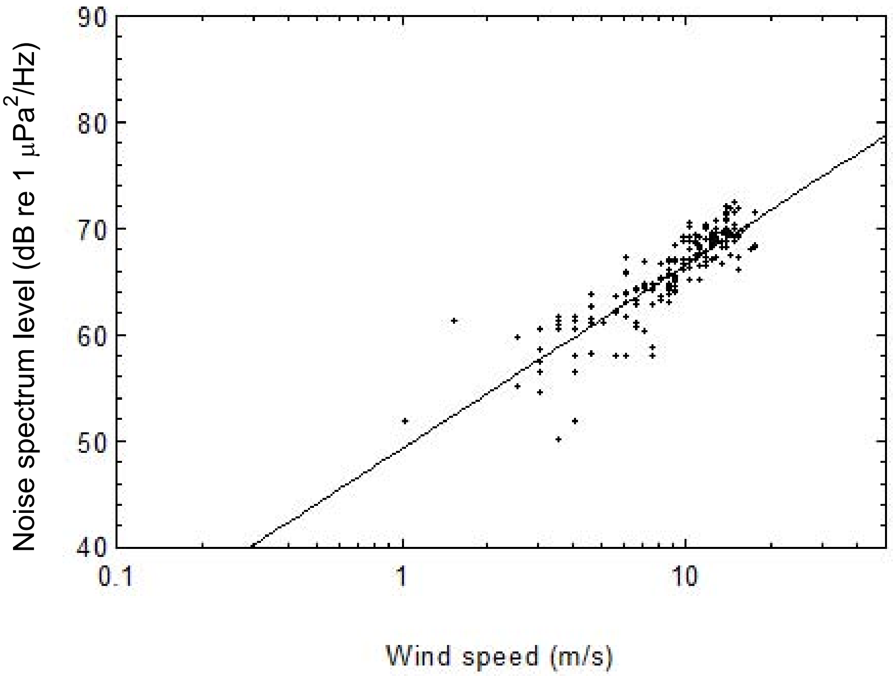

Figure 2: Noise at 1 kHz off Perth, Australia as a function of wind speed at Rottnest Island, 55 km from the hydrophone.

While the noise from breaking waves is well correlated with wind speed, the values of A and n vary significantly with location. This is partly due to the variation with location of the influence of non wind-dependent noise, as discussed above. It also seems likely that the surface wave characteristics have some secondary effect on wind-dependent noise production, even though wind seems to be the primary cause. The noise produced depends on the factors that cause waves to break and these in turn are not just wind speed but characteristics of the waves themselves. The amount of swell, the direction of the wave field relative to the wind and the fetch and duration of the wind may all have an effect. Indeed, it is surprising that the correlation of noise with wind speed is as good as it is. Another source of variation is the propagation. Even though the sources of wind-dependent noise tend to be relatively local, different propagation conditions can vary both the area of sources contributing and the loss on propagation to the receiver [e.g., 17, 18]. Hence it is usually desirable to determine the dependence of noise on wind speed for particular locations. Figure 3 shows the range of average wind-dependent noise estimates for waters around Australia [19]. This is the best estimate from data from various locations. There is greater uncertainty at lower frequencies.

2.3.2 TRAFFIC NOISE

Once the wind-dependent noise component has been established, the sources of the non-wind-dependent component need to be determined. Non wind-dependent noise can be determined by interpretation of plots like Figure 2 to estimate the range of data that does not show a dependence on wind speed. The uncertainty in determining the relative contribution of wind-dependent noise and non wind-dependent noise in each data point makes this difficult, especially since there is usually a spread of likely values for each component. For example, there is significant temporal variation in non wind-dependent noise.

At low frequencies (below about 200 Hz), the non-wind dependent noise is likely to be traffic noise but there can be significant contribution from biological sources. Fish and some baleen whales produce sounds at these frequencies. Traffic noise is nondescript in character and has a spectral shape similar to that of low frequency wind-dependent noise. Hence identification of traffic noise from the acoustic characteristics of the noise alone is generally not possible on a single hydrophone (a multi element highly directional array may be able to separate some individual ship sources as a diagnostic). Low frequency biological noise is more distinctive (see section 2.3.3) and thus traffic noise may be estimated to be what remains after wind-dependent and biological noise are removed, though it is always possible that some other unknown sources are contributing. Figure 3 shows estimates of traffic noise from regions around Australia [19] where there is substantial variation in traffic noise, more than around the U.K., Europe and North America. The estimates are broadly consistent with shipping densities and propagation conditions. The highest levels are comparable to the "usual traffic noise" of Wenz [3]. The estimate for the shallow Arafura and Timor Seas north of Australia is probably not actually traffic noise but rather residual noise from other sources, given the very low shipping densities and poor propagation.

2.3.3 BIOLOGICAL NOISE

The biological contribution to ambient noise is most significant when large numbers of animals are calling and, at times, there are so many calls that they merge into a continuous noise. These are usually referred to as choruses. Individual biological sounds, however, are transients, and this is a very useful diagnostic feature. It is possible to identify the noise as biological and usually to identify the type of animal responsible by detecting and analysing the individual transient calls. For example, many choruses rise and fall in level over some time period, a common example being the "evening chorus" which rises after sunset and lasts a few hours [10, 11, 12, 13]. Initially individual calls are heard, then the numbers of calls increase and the chorus level increases until the sounds merge into a continuous noise. The individual sounds, detectable early or late in the chorus during the rise of fall can be used to identify the sources. Few biological contributions to the ambient noise are continuous over large time scales but one of the most widely observed choruses is: that from snapping shrimps which abound in shallow warm waters. Shrimp choruses are usually continuous with only small temporal variations in level. Individual shrimp clicks, however, are usually detectable from closer animals, providing a distinctive character to the noise. Figure 3 shows some examples of choruses in the Australian region.

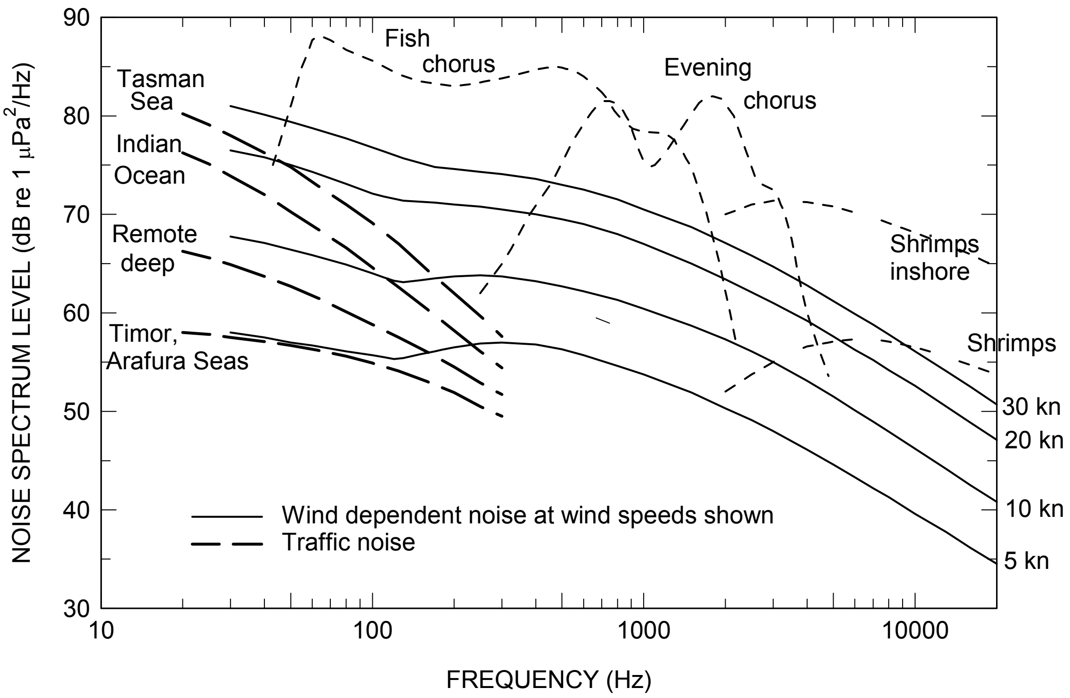

Figure 3. Summary of ambient noise spectra for the Australian region showing a wide range of traffic noise levels and biological choruses.

2.4 AMBIENT NOISE AND MARINE ANIMALS

Marine animals make extensive use of sound because visibility and dispersal of scents are generally so limited in the ocean compared to atmosphere. On the other hand, sound travels with far less absorption loss, and thus propagates much further underwater than it does in air. There is a view that marine animals live in an ideal acoustic environment, communicating over great distances. This has led to concern that the introduction of anthropogenic noise to ambient has significantly limited marine animal communication, a concern that is especially expressed for whales. In particular, since traffic noise tends to dominate the ambient noise at low frequencies, there is concern that traffic noise has significantly limited communication of baleen whales, many of which produce sounds at frequencies similar to those where traffic noise dominates.

However, those who are familiar with applications of underwater sound (usually one or other form of sonar) are well aware that the ocean is by no means an ideal environment for use of sound. In particular, such good propagation means that sound travels to great distances not just from the source of interest, but from all other sources, and the noise from all these other sources provides a high and variable background noise: the ambient noise. Signals have to be detected against this background noise, so there is not necessarily an advantage in animal communication for propagation to be so good.

The variability of ambient noise causes substantial variability in detection range. An increase in noise needs to be offset by a decrease in propagation loss of the same amount to maintain the same signal to noise ratio at the receiver. Propagation loss usually increases with distance, so that higher noise is offset by smaller source to receiver distances. A variation of 20 dB in ambient noise level is not uncommon and to offset this by varying the propagation loss by the same amount would vary the range for which a signal is audible by a factor of 10 for typical propagation loss in the ocean (spherical spreading – it would be an even larger factor for lesser rates of propagation loss). Propagation of sound in the ocean is also very variable and so adds to the overall variability in detection range. Hence marine animals have to cope with variations in aural detection range significantly greater than a factor of 10.

Marine animals are often in situations where there are many conspecifics calling nearby. When animals call in large aggregations to form choruses, the noise of the choruses may dominate the ambient noise for kilometres [11, 13] and will be even higher within the mass of calling animals. Chorusing is a sufficiently common event from a wide range of species of invertebrates, fish and marine mammals to be considered an important component of the long term noise exposure experienced by the animals, whether from surrounding conspecifics or from other species.

The concern that traffic noise may be limiting communication of baleen whales arose from extrapolation of the classic wind-dependent noise curves of Wenz [3] to low frequencies which resulted in levels that were well below traffic noise levels. Wenz' wind-dependent noise spectra show a broad peak at around 500 Hz with levels decreasing with decreasing frequency down to their lower limit of 100 to 200 Hz (from high to low winds speeds, respectively). This led to the idea that there was a "noise notch" at low frequencies that was exploited for communication by baleen whales, especially the blue and fin whales which produce sounds at frequencies below 100 Hz, and that traffic noise has severely compromised their ability to communicate, at least over long distances. The difficulty in testing this idea is that most measurements of ambient noise have been made in areas of high shipping densities and thus high traffic noise, and it has been difficult to determine the characteristics of natural ambient noise at these frequencies.

The wind-dependent noise curves of Figure 3, measured in areas of low traffic noise, show that noise levels rise with decreasing frequency below 100 – 200 Hz, while still showing evidence of the broad peak at around 500 Hz. These results are consistent with the few results in early and recent work in areas around North America where traffic noise was less significant than usual [e.g. 7]. Wenz also noted the wind dependence at low wind speeds and some of the data presented show similar spectral shapes to those of Figure 3. At 30 knots the low frequency wind-dependent noise levels in Figure 3 are comparable to upper levels of "usual traffic noise" given by Wenz. Some areas, however, may show higher levels of traffic noise and there is concern that traffic noise levels may have risen since Wenz' measurements. For example, ambient noise measurements off Pt. Sur, California show higher noise levels at low frequencies at the 50 percentile and they considered that a large proportion of this is due to shipping [20].

Marine animals have evolved to cope with the wide range of ambient noise and the variable acoustic environment of the ocean. Understanding the characteristics of ambient noise and its range of variation provides a context for assessing the impacts of anthropogenic noise.

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