AUSTRALIAN RESEARCH IN AMBIENT SEA NOISE

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ABSTRACT: Ambient noise in the ocean results from the contributions of many different sources and varies over a wide range of levels, more than 20 dB variation being common. It causes a wide variation in sonar performance and prediction methods are required for the effective design, acquisition and operation of sonars. Ambient noise in Australian waters is substantially different to that in the waters around North America and Europe where most earlier measurements of noise were made. Consequently, ambient noise prediction methods developed in the northern hemisphere are of limited use in Australian waters and there has been a continuing, though low level, research effort to categorise ambient noise in this part of the world. This paper reviews recent research on ambient noise in Australian waters in the context of earlier work. The main components of ambient noise are the noise of breaking waves at the sea surface and the noise of the marine animals. Distant shipping traffic and rain on the sea surface are also significant. Lower levels of traffic noise in this part of the world have revealed aspects of natural noise not examined elsewhere. The extraordinary range and variety of marine animal sounds are of particular interest both in the impact on sonar and the significance in animal behaviour.

1. INTRODUCTION

Ambient sea noise is the acoustic background noise in the ocean from all sources. It is of interest in its own right in terms of what we can learn about ocean processes and communication and behaviour of marine animals. It is also a major limitation on sonar performance since signals must be detected against this ambient noise. We and the marine animals use sound extensively in the ocean because under most conditions, it is the most effective means of transmitting information over any distance through water. Shallow, clear waters, such as those of the Great Barrier Reef are exceptions where light and vision play a major role. Even so, sound is used extensively by animals in such environments. Under most conditions, electromagnetic radiation is so limited by absorption of energy in water that it is effective only over very short ranges. Sound, on the other hand, loses very little energy in water by absorption, at least in the audio frequency range, and travels to great distances, some sources being detectable across the full width of an ocean basin. This very low absorption contrasts with the conditions in air where the high absorption rate causes sound to be generally a local phenomenon, most sources being effective over distances of metres to tens of metres. Sound travels two orders of magnitude farther in water than in air for the same amount of absorption attenuation.

While the transparency of the ocean to sound allows transmission over large distances, it also means that sources at large distances (up to tens and sometimes hundreds of kilometres) contribute to the ambient noise, leading to high and very variable ambient noise levels. It is common for ambient background noise, excluding contributions from close sources, to vary over a range of about 20 dB as a result of varying weather conditions, distant shipping densities or biological behaviour or habitat, and this variation may be temporal, seasonal or geographical. The full range of variation of ambient noise, however is more than 30 dB, and ambient noise levels over the frequency band 50 Hz to 10 kHz are typically in the range 90-120 dB re 1 mPa. This variation applies to the background noise and does not include the much wider variation caused by close sources such as a passing ship. A change of 20 dB in noise level will change the propagation loss that can be tolerated at the threshold of detection of a sonar by an amount that typically corresponds to a factor of 10 in range (though is quite variable). Ambient noise is the main component of background noise in passive sonars, dominating in most but the quietest conditions, so is critical to its performance. Ambient noise is less of a limitation on active sonar, since it is reverberation limited for shorter range targets, though there have been examples where active sonar performance was so degraded by ambient noise that it was barely effective. These comments apply whether the sonar is man made or the acoustic function of an animal.

Because of the major effect on sonar performance, it is routine for sonar operators to make ambient noise predictions to estimate the detection ranges they can expect to achieve for the prevailing conditions. The wide variations in noise and thus sonar performance can be exploited tactically in naval operations, and computer based prediction systems are now used for this purpose. Most sonars are designed for waters around north America and Europe where ambient noise is significantly different to that of the warmer waters around Australia. Some sonars have needed significant modification to perform effectively in Australian waters.

The early research into ambient noise was concentrated around North America and Europe. Ambient noise is substantially different in the Australian region because of environmental differences so there has been a continuing research program aimed at understanding and predicting the noise for Australian conditions. Some aspects of ambient noise would be expected to be common to all environments, an example being the noise of breaking waves, so our research has also contributed to universal knowledge of ambient noise and has been able to build on results from other parts of the world. Nevertheless, even after 60 years of research world wide, there remains a lot that is not understood about ambient noise.

While it is generally recognised that ambient noise is a limitation on sonar performance, there are conceptual difficulties in dealing with this problem. The first is the failure to understand that the noise varies over such a wide range that a few spot measurements at a location are almost useless in typifying the ambient noise at that location. The other is that the noise has only a weak dependence on position: it varies far more with time. The noise depends on the weather as it influences sea conditions and on the behaviour, distribution and migrations of marine animals. The dependence on position and time is so complex that there is little point in trying "map" ambient noise from routine data collection over the waters of interest, even if we had the enormous resources required. Consequently, our approach has been to understand the phenomena, the physical processes that generate the noise and the behaviour of the biological sources. Noise prediction depends on distilling the resulting knowledge to relatively simple relationships between the components of noise and readily available variables. For example, noise from breaking waves can be predicted from wind speed, and consequently changes in noise can be forecast from weather forecasts. Biological noise can be predicted from known behaviour, migration and habitats of marine mammals, once their acoustic behaviours are known.

Early Work

The first significant study of ambient noise was conducted during the second world war in response to degradation of sonar performance caused by unidentified noise. It was not known at the time whether this was jamming by the enemy or natural noise. The study showed that in fact it was the natural ambient noise (the sounds of shrimps) and the resulting publications (Knudsen, Alford and Emling, 1944, 1948) provided a remarkably comprehensive summary of the major components of ambient noise. The noise prediction curves — the "Knudsen curves" — are still sometimes quoted today. They identified the main components of noise in shallow water as (a) water motion near the sea surface (breaking waves), (b) marine life and (c) ships. Noise from breaking waves was related to sea state. Noise from marine life included choruses such as the wide spread noise of snapping shrimps that abound in shallow water.

Wenz (1962) refined the interpretation of the ambient noise, based on a large series of measurements. He presented "traffic noise" spectra which he defined as the background noise from many ships, none of which was detectable as such. This resulted from contributions from a large number of ships over distances of hundreds of kilometres and provided a general low frequency background, with a spectral slope of -3 to -6 dB per octave, falling below other components above 100-200 Hz. Traffic noise around Australia varies widely, generally in accordance with the shipping densities and propagation conditions (Cato, 1978). Wenz also presented revised sea surface noise spectra as "wind dependent noise," having a broad peak at around 500 Hz and differing significantly from the Knudsen curves below this frequency. Relating breaking wave noise to wind speed rather than wave height may be counter intuitive, but further studies (e.g. Perrone, 1969) supported this. The noise correlates much better with wind speed than with any measure of wave height. It is the action of wind that causes sea surface waves, but it takes many hours for a sea to develop fully, and the wave height at any time depends on the wind speed, on the wind duration and on the fetch. If the wind drops, it may take hours for the waves to diminish but the breaking of waves and the noise generated drops concurrently with the wind.

2. NOISE GENERATED BY SEA SURFACE MOTION

Any motion of a fluid interface that is a discontinuity in density or sound speed generates sound, and the source strength depends on the difference in the product of density and sound speed squared (i.e. difference in the inverse of compressibility) either side of the interface (Cato, 1991a). There are a number of such interfaces in the vicinity of the sea surface with large differences in density and sound speed, so each are potentially significant sources of sound. A simple example is the oscillation of an air bubble in water, which has been extensively studied in classical acoustics (Minnaert, 1933).

Noise of Breaking Waves — Wind-Dependent Noise

Although this was recognised as a major component of noise in the earliest studies, it was not until the late 1980s that the source mechanism was determined. Laboratory experiments by Banner and Cato (1988) using a simple breaking wave showed that the noise resulted from the oscillation of bubbles immediately on formation by air entrainment as the wave broke. Further experiments built on this work (Medwin and Beaky, 1989; Pumphrey and Ffowcs Williams, 1990) providing further evidence of the source characteristics. Observations of individual breaking waves at sea were consistent with these results, though the individual bubble contribution could not be detected (Updegraff and Anderson, 1991).

Air is entrained in the breaking wave and is compressed by the weight of the overlying water to pressures greater than the surrounding water pressure. The excess pressure causes the air to expand to form a bubble, and as it expands the momentum carries it on beyond the size at which the internal pressure matches the water pressure, resulting in lightly damped oscillation. Since the bubble oscillates volumetrically it is a monopole source, and few natural sources of sound are so efficient. The proximity to the sea surface, however, changes the radiation pattern to effectively that of a dipole, since reflection from the surface provides almost perfect reflection with a phase reversal, i.e. an out of phase surface image. This results in breaking wave noise radiating preferentially downward, as Ferguson and Wyllie (1987) have shown experimentally.

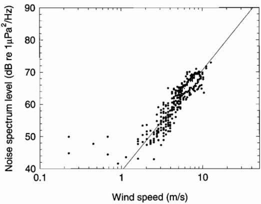

Figure 1. Noise from breaking waves at the sea surface as function of wind speed (spectrum level averaged over the 1/3 octave band centred at 1 kHz). Measurements were made at a fixed position in Spencer Gulf where there is little contribution from other sources. There are more than 500 data points.

An example of the dependence of noise on wind speed in Spencer Gulf, South Australia, is shown in Fig. 1 (Cato et al. 1995). Such a good correlation (coefficient 0.93) is, however, an unusual result. Spencer Gulf is an unusually quiet site, with little noise from other sources, so that wind dependent noise is evident for wind speeds as low as 2 m/s. In the open ocean, other sources of noise such as traffic noise dominate at low wind speeds and the contamination of these sources results in a poorer correlation of noise with wind speed and a regression line with a lower slope than in Fig. 1, since other sources of noise contribute at the lower wind speeds in a way that is not possible to remove. The slope of the regression line in Fig. 1 gives noise intensity as proportional to the cube of the wind speed consistent with the dependence of wave breaking on wind speed.

Typical spectra of this component of wind dependent noise were given by Wenz (1962), and similar spectra have been measured in many subsequent studies. It shows a broad peak at about 500 Hz and is usually dominant from about 100 Hz to some tens of kilohertz. The characteristics of the received noise field depend on the propagation of sound as well as on the source characteristics. Since breaking wave sources radiate preferentially downwards, the steeper rays carry the most energy and multiple bottom and surface reflections are required for contributions beyond a fairly local region. Thus the area of sources contributing to the field at a receiver varies substantially with the reflectivity of the bottom. For a completely absorbing bottom, 90% of the noise energy comes from sources in a circular area with a radius three times the water depth (Cato and Tavener, 1997a). A reflective bottom expands this area substantially, and modelling by Kuperman and Ingenito (1980), Chapman (1987) and Harrison (1996) indicate that the variation in the effective area of sources may vary by at least an order of magnitude. Since bottom reflectivity is frequency dependent, the spectral shapes of the received noise may also vary.

A wide variation in wind dependent noise between locations is in fact observed. Usually the correlation of noise on wind speed is poorer than that of Fig. 1, the slopes of the regression lines vary as do the spectral shapes (there are significant differences between Spencer Gulf and waters off Perth for example: Cato, 1997; Cato and Tavener, 1997b). Some of this variation may be due to the unknown influence of the surface wave properties, some is due to contamination of measurements by other sources of noise, but much is likely to be due to variations in propagation conditions. Better prediction of wind dependent noise requires the development of a model of the source field and matching of this to a propagation model to calculate the received noise field. Since the measurements that we have to work with in the ocean are of the received noise field, we need methods of inverting these measurements to estimate the source field characteristics, thus removing the effect of propagation at the site of measurements. This is a difficult experiment because of the precision of the measurements required in the received noise field and the detailed knowledge of the bottom acoustics needed.

Low Frequency Wind-Dependent Noise

This is the dominant prevailing component of ambient noise at frequencies below about 200 Hz in the Australian region and probably in much of the world, but it does not appear in noise prediction methods from the northern hemisphere. The reason is that the northern hemisphere methods were derived from measurements in waters of high shipping densities so that the high levels of traffic noise made this component difficult to detect. The spectral slope of -3 to -6 dB per octave is similar to that of traffic noise and there is nothing in the characteristics of the noise to distinguish it from sea surface generated noise. Both result from such a large number of sources that any individual characteristics are lost. The lower levels of traffic noise in a Australian waters have allowed us to measure this component by determining the dependence of noise on wind speed (Cato, 1978; Burgess and Kewley, 1983; Cato and Tavener, 1997b). Evidence of this component can be seen in a few North American studies, particularly those of Piggot (1964). Wenz (1962) noted evidence of this component in some of his data, but did not include it in his prediction methods, presumably through lack of data. Examples of the wind dependent noise spectra (with both components combined) measured in Australian waters are shown in Fig. 2 (Cato and Tavener, 1997b).

This is a good example of differences in environmental data between Australian and northern hemisphere studies, even where the actual property of the environment could be expected to be similar. This component causes ambient noise to vary with wind speed by more than 20 dB in Australian waters, but none of this would be predicted using northern hemisphere methods. It turns out that at winds of 15-20 m/s, this component of surface noise is comparable to the high levels of traffic noise in Northern American waters.

While the source of this low frequency noise has yet to be determined, a likely cause is the oscillation of bubble clouds as

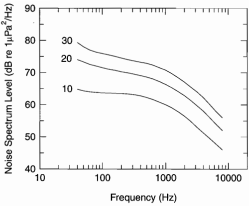

Figure 2. Averaged sea surface noise spectra at the wind speeds shown in knots, measured off Perth.

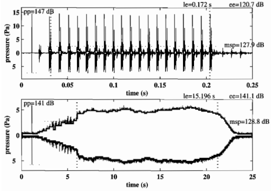

Figure 3. (Top) Call from a fish of the family Terapontidae (McCauley 2001), and (bottom) call from a blue whale (McCauley et al 2001), showing several types of call level descriptors. Note the two orders of magnitude difference in the time scales. Abbreviations are: pp = peak-peak (dB re 1mPa); ee = equivalent energy (dB re 1mPa2.s); msp = mean squared pressure (dB re 1mPa); le = call length (s) as defined by time taken between 5 and 95% of the energy to pass (with these time bounds shown by the vertical dotted lines). Trailing surface reflections are evident in the fish call.

proposed by Prosperetti (1988) and Carey and Browning (1988). Large numbers of bubbles formed by a breaking wave might oscillate collectively, effectively like one large bubble. The cloud has a lower sound speed due to the entrained air and thus lower compressibility, forming an effective large volume source.

3. BIOLOGICAL NOISE

Because marine animals make extensive use of sound, a substantial part of the ambient noise is biological. Individual biological sounds vary from a few microseconds duration at frequencies up to hundreds of kilohertz (snapping shrimps: Everest et al. 1948; Cato and Bell, 1992; dolphins: Au 1993) to 15 to 20 s duration at frequencies as low as 20 Hz (blue whales: Cummings and Thompson, 1971; McCauley et al. 2000a). The sounds of most animals, however, are within the audio frequency range and durations lie between 0.1 to 5 s. Examples of the wave forms of a fish and a whale call, illustrating differences in signal length and measures of signal magnitude are shown in Fig. 3. Individual sounds are detectable as signals by sonars and must be separated from signals of interest. Many animals call repeatedly for hours, causing interference over a long period, both to sonar and presumably, to other marine animals. Some animals occur in such large numbers that, calling en masse, they produce a continuous component of the ambient background noise, referred to as a chorus.

The importance of biological noise was recognised in the earliest studies of ambient noise (Knudsen at al, 1944, 1948), but biological noise is generally not well represented in ambient noise prediction methods developed for the northern hemisphere. In Australian waters, biological noise is so substantial and wide spread that no prediction method would be adequate without the biological noise component. The difference is partly due to differences in the environments — Australian waters are warmer and include a substantial amount of tropical water, and there has been a greater interest in shallow water.

In shallow tropical waters near Australia, biological noise is a major component over most of the frequency band from about 50 Hz to hundreds of kilohertz, and dominates at low wind speeds (Cato, 1980, 1992). It is only during heavy rain that the biological contribution ceases to be important. Biological choruses from large numbers of individuals calling are wide spread in temperate as well as tropical waters, and these regularly cause variations in noise level of more than 20 dB over periods of a few hours or more (Cato, 1978; McCauley and Cato, 2000).

The marine mammals produce the highest source level sounds and are the main sources of transient signals, while fish and invertebrates tend to be the main sources of choruses, though whales also produce choruses. There is, however, no clear dividing line and as transients become more numerous, they contribute significantly to the background noise.

Marine Mammal Sounds

Marine mammals, especially whales, are the main sources of intense transients. Whale numbers in Australian waters have been steadily increasing over the last three decades, and the general increase in the contribution to the ambient noise over this time has been very evident. The rate of increase shows no signs of abating. The main contributors to the ambient noise in Australian waters are humpback whales, blue whales and sperm whales, and to a lesser extent, dolphins.

Humpback whales

Humpback whales migrate annually along the east and west coast of Australia, between the summer feeding grounds in Antarctic waters and the winter breeding grounds inside the Great Barrier Reef on the east coast and on the northwest shelf and Kimberleys on the west coast (Chittleborough, 1965;

Dawbin, 1966; Jenner et al. 2001). Numbers have been increasing at a rate of more than 10% pa for decades (Bryden et al., 1996; Paterson et al., 1994, 2001; Bannister and Heldey, 2001). The population estimates for 1999 are 3,600 (± 440) for the east coast (Paterson et al., 2001) and between 8,200 and 13,600 for the west coast (Bannister and Hedley, 2001). These are still significantly less than the estimated pre-whaling populations, less than half for the east coast stock (Chittleborough, 1965). At the end of whaling in 1962, the east coast population may have been as low as 100 (Paterson, et al. 1994) indicating the substantial recovery that has taken place.

Humpback whales probably also migrate further off shore, since there are breeding grounds near tropical islands and reefs of the South Pacific, but not much is known about these migrations. Off the coasts of Australia, the timing of the migrations are quite predictable, with the time of the peak off Brisbane varying by less that a few weeks (Paterson et al., 2001). At this latitude, half the stock passes within the four weeks of the peak which occurs in late June early July going north and in late September, early October going south (Chittleborough, 1965; Paterson et al., 2001).

Male humpback whales produce a complicated song of repeated phrases within a pattern of themes. Typical song durations are about 10 min, although individuals may sing for hours at a time (Payne and McVay, 1971; Cato, 1991b). About 5% of passing whales sing going north at latitudes of Brisbane (Cato et al., 2001) and about 13% going south (Cato et al., 2001; Noad and Cato, 2001). The effect on ambient noise is now substantial. Two decades ago, humpback whale sounds were detectable occasionally during the migration, whereas today, several singers would be audible at any time. Humpback whale sounds are thus a common cause of transient signals, and are approaching the point where they will form choruses as is observed on the Hawaiian breeding grounds (Au et al., 2000), and was observed off the north island of New Zealand in the late 1950s, before numbers were reduced by whaling.

At any given time a local humpback whale song may contain a repertoire of in excess of 30 individual sound types, structured into a song. These sound types can range through broad band clicks, high frequency whistles to deep bellows or moans of many seconds duration. In general, most of the energy in the humpback song lies within the frequency range 30-2500 Hz, with that of the most predominant sound types in the band 100-500 Hz, though harmonics may range as high as 12 kHz. Some sound types, such as the high frequency whistles, are typically transmitted at low levels, whereas others are transmitted at much higher intensities. McCauley et al. (1996) in a study of humpback song in the 20-30 m deep Hervey Bay in Queensland, estimated that under low ambient noise conditions the higher frequency whistles would have fallen below audibility at ranges greater than about one kilometre, while the more powerful low frequency components would have been audible to tens of kilometres.

Although all humpback whales within a stock sing basically the same song at any time, the songs — both the sounds and the structure — change progressively with time. Such change requires continual copying between individuals. Sounds are so well matched during copying that differences between individuals are little more that those within the song of an individual (Macknight, 2001). Changes are usually detectable over time scales of a few weeks, but the rate of change is variable. Over some years, there may be only minor changes in some of the sound types, while over other years, substantial changes in most sound types and in the song structure occur (Payne et al. 1985; Cato, 1991b; Dawbin and Eyre, 1991). These changes are spread through the stock. Only the broad rules that govern the song structure seem to be fixed, though even these can sometimes break down as in 1984 off the east coast (Cato, 1991b).

Songs separated by thousands of kilometres along the length of the coastal migration paths have been observed to be the same at any time (Cato, 1991b), indicating that, for a particular migration path, the song is basically the same. Song off east Australia, New Caledonia, New Zealand and Tonga are similar, the differences increasing with separation (Helweg et al., 1998), indicating that there is sufficient interchange between migrations separated by open ocean to maintain similar songs even with continual progressive changes in the songs. Migration paths separated by the Australian continent, however, generally have unrelated songs (based on comparisons within the same year for a number of years: Cato, 1991b; Dawbin and Eyre, 1991), even though there is a small interchange between stocks (Chittleborough, 1965; Dawbin, 1966). In 1997, however, the west coast song was heard from a small percentage of singers off the east coast. By the end of 1998, the west coast song had completely displaced the east coast song (Noad et al., 2000). Such revolutionary change appears to be previously unknown for culturally transmitted signals of any animal.

As well as the complex and stereotyped song produced by humpback whales they are also capable of producing a broad range of other sound types, which may be used in social encounters. For example several non-song sound types may be occasionally heard from cow-calf pairs or interacting males. The sound of a breaching whale is audible for significant distances (described as "a rifle shot" by McCauley et al. 1996), and has been likened to the sounds produced by air-guns used in offshore petroleum exploration (McCauley et al. 2000b). In trials approaching whales with a single air-gun in Exmouth Gulf, McCauley et al. (2000b) found that in more than half the trials carried out, non-target whales consistently charged towards the operating air-gun, investigated it, then swam off. They speculated that these were probably male animals who considered the air-gun signal as an indication of nearby breaching or an acoustic event worth investigating.

Blue whales

The low frequency, intense tonal signals of blue whales have been extensively studied in the north Pacific. Similar 20 Hz tones were recorded off New Zealand in the 1960s (Kibblewhite et al., 1967). These were believed to be from blue whales. It has only recently been realised that in some parts of Australia, blue whales can dominate the low frequency ambient noise for months on end. Off Western Australia, what are believed to be pygmy blue whales produce a sequence of three stereotyped signals in a 'song', with dominant energy over 18-26 Hz but harmonics and a secondary source extending up to 100 Hz (McCauley et al. 2001). Each component is approximately 43, 23 and 20 s long respectively, which together run for around 120 s. Sound propagation estimates, indicate these signals may transmit into the hundreds of kilometres along deeper waters off the shelf edge. Up to nine callers have been reported at any given time, and calls are twice as frequent at night as during the day (McCauley et al. 2001).

Sperm whales

Sperm whales produce intense clicking sounds with most energy over the frequency band of 1 to 10 kHz. Recent measurements have estimated the mean square source level to be 233 dB re 1 μPa at 1 m (Møhl, 2001), the highest source level of any marine animal. Sperm whales were one of the main targets of whaling, but were so plentiful that the effect of whaling was less devastating than it was for some of the large baleen whales, such as the blue, right and humpback whales. Sperm whales are often found in large schools (Paterson, 1986), many whales producing the intense clicking sounds and making a substantial contribution to the background noise.

Fish Sounds

The significance of fish sounds to ambient noise was recognised in early studies (Knudsen et al., 1984) where it was found that fish commonly known as croakers (Scianidae) in the United States produced choruses. It became apparent in the many studies that followed, that many species of fish produce a wide variety of sounds, usually over the frequency band from about 50 Hz to 4 kHz (Fish, 1964; Tavolga 1964 & 1967, Winn 1964; Moulton, 1964; Fish and Mowbray, 1970 ; Fish and Cummings 1972).

There is a similarly wide variety of sounds from fish in Australian tropical waters, from harmonic sounds like fog horns to knocking and drumming sounds (Cato, 1980; McCauley and Cato 2000; McCauley, 2001) and these produce a substantial component of the back ground noise in tropical waters at low winds speeds, and in the absence of heavy rain. Almost all of the fish groups studied for sound production have shown daily, lunar, seasonal and spatial patterns in their sound production.

For example in northern Australia, nocturnally active fishes have been reported to consistently raise ambient noise levels by an average of 15 dB above normal levels over the frequency range 300-900 Hz about coral reef systems (McCauley and Cato, 2000; McCauley, 2001). On occasions, usually associated with new moon periods over summer months, choruses of these fish have been measured up to 30 dB above normal ambient levels. These choruses are regular, persistent and cover a huge geographical extent, indicating their importance to ambient sea noise predictions and to the fish concerned.

Invertebrate Sounds

The best known and most ubiquitous invertebrate sound is that of the snapping shrimp, which abounds in shallow warm waters, (Knudsen et al., 1948; Everest et al., 1948). It has been known since the earliest studies (Brown Goode, 1878) that the sound is produced when the shrimp snaps an oversized claw, but it has only recently been shown that the source of the sound is actually the collapse of a cavitation bubble formed in the wake of the snapping claw (Versluis et al., 2000). These shrimps abound in such large numbers that the snap sounds form a continuous crackling background noise, evident in Australian shallow waters at all times of day (Cato, 1980; McCauley, 1994; Readhead, 1997). An individual snap is about 10 ms duration, and the noise extends from about 1 kHz to beyond 300 kHz (Cato and Bell, 1992).

Biological Choruses

When large numbers of animals call en masse, they produce a sustained component of the ambient noise known as a chorus. Knudsen et al. (1948) and Fish (1964) described choruses from a number of sources, including shrimps, fish and sea urchins. Choruses from most species occur for a few hours of the day, usually the same hours each day, in contrast to that from snapping shrimps which show only a small diurnal variation.

Ambient noise studies around Australia have shown that choruses are widespread in both temperate and tropical water (Cato, 1978; McCauley and Cato, 2000; McCauley 2001). In shallow and shelf edge waters, an evening chorus, occurring for a few hours between sunset and midnight is almost always observed, and is usually so regular as to be highly predictable. In some locations, there is an early morning chorus in the few hours before dawn. The noise level rises to levels of 20 dB or more above the background during the chorus, and at the height, there are so many sounds that they merge into a nondescript roar. These choruses are from fish and invertebrates, some apparently related to feeding and have most energy between 500 Hz and 4 kHz. Fish also produce choruses in more complicated diurnal and seasonal patterns, related spawning behaviour. The season and time of day of calling varies with species (McCauley, 2001). In a study area where up to four chorus types may have been potentially heard at the same time, the displacement in time of choruses or time of maximum calling rate, appeared to limit competition for the 'sound space' (McCauley, 2001).

While the evening chorus has been observed in deep water at a number of locations, these have been within 6 km of shallow water, so may have been from animals in shallow water habitats. Fish choruses in which individual sounds were detectable have been observed in deep water large distances from shallow water (Cato, 1978; Kelly et al., 1985).

Sperm whales are common sources of sustained choruses in deep water, with frequency band extending from 500 Hz to beyond 5 kHz (Cato, 1978). While these have a similar spectrum to the evening chorus, the characteristic clicking sounds are always clearly detectable, and although there may be many clicks per second, a rhythmic beat of a half second period is often evident. Sperm whale choruses are not so regular as fish and invertebrate choruses, the locations depending on the movements of the whales in search of prey, though there appear to be preferred feeding areas, such as the deep waters off Kaikoura, New Zealand, where there is a whale watch industry. These choruses may continue for many hours at a time.

CONCLUSIONS

A wide variety of sounds from many different types of sources contribute to the ambient noise in the ocean. The area of sources contributing is large because of the good propagation of sound in the ocean and noise levels vary widely as conditions and the behaviour of the sources change. This causes substantial variation in sonar performance and provides a challenge to those who need to predict the effects on this performance. The pioneering studies of ambient noise in waters around North America and Europe provided the basic knowledge of ambient noise, but the significant environmental differences in Australian waters have required substantial research to adequately characterise the ambient noise here. This research has covered a range of disciplines from fluid dynamics to animal behaviour, addressing sources such as wave breaking at the sea surface and marine animals. While much of the work has been driven by the need to operate sonar effectively in our waters, it is apparent that the noise can be used to learn more about physical processes such as wave breaking and rain on the sea surface, and biological processes such as marine animal behaviour, movements and abundance. For example, whales can be heard at much greater distances than they can be seen, so acoustics is turning out to be a useful tool in studies of behaviour and abundance. The increase in whale numbers over the last two decades has substantially increased their contribution to the ambient noise. There are still many unknowns about ambient noise and limitations on our ability to predict and forecast the noise. Some sounds, apparently from marine mammals, have yet to be identified.

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