Effects of Climate Change and Anthropogenic Ocean Acidification on Underwater Acoustic Communications

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***Abstract*—Global climate change is a widely accepted phenomenon and it is well understood that it is also leading to changes in the oceanic conditions. Increased industrial activities have also led to anthropogenic ocean acidification, the effects of which, on marine ecosystems, is a vigorously investigated topic. However, the impact of these phenomenon on underwater acoustic communication has not been investigated thoroughly. Fluctuations in ambient ocean conditions, such as salinity, acidity and temperature can lead to changes in the underwater acoustic channel performance. Since both marine mammals and man-made underwater wireless networks depend upon acoustic communications it is important to understand the effects in this context as well. An insight into the effects of climate change and anthropogenic ocean acidification could aid in designing better communication systems and also help explain some observed changes in marine mammal communication behavior. In this paper we present the results of a study conducted to better understand the effects of global climate change. Along with a brief presentation of the mathematical model, results of increasing temperature and acidity are discussed and effects on digital and marine mammal communication are both explored.**

I. Introduction

The scientific community widely acknowledges that industrialization is leading to a global climate change as a result of increased CO_2, CH_4 and other greenhouse gasses in the atmosphere. The average temperature increase and anthropogenic ocean acidification are phenomenon that have been observed over many years. Effects on marine life due to these rapid changes are anticipated and vigorously researched. Biological processes such as calcification and respiration of deep-sea animals are already expected to be negatively effected. In fact, the ocean acidification process is leading to changes in the geophysical properties of the ocean as well. Similar effort has not been invested into exploring the effects of climate change and ocean acidification on the underwater acoustic channel, which is widely used for communication by marine mammals and underwater wireless networks.

The dependence of sound absorption upon factors such as pH and ambient temperature is a known phenomenon [1]. These acoustic relaxations are introduced mainly because of geochemical cycles related primarily to boric acid and magnesium sulphate and mathematical models have been developed to incorporate these relaxation effects into predicting sound absorption [1], [2]. However, increasing pH and temperature are not only responsible for changes in the absorption mechanism, but they are also contributing to increased ambient noise, change in optimal transmission frequencies and other hitherto unexplored effects.

It is estimated that since the pre-industrial era to the 1990s the surface ocean pH reduced by less than 0.1. Though this rate does not seem alarming according to the projections of the Intergovernmental Panel on Climate Change (IPCC) it is expected to reduce by over 0.2 by the middle of this century [3]. In fact, according to some models it is expected to increase rapidly as the oceans take up more anthropogenic CO_2 from the atmosphere, thereby, dropping by up to 0.5 units within this century [4]. Some reports claim that this problem may accelerate even faster [5].

Further compounding the problem is the globally observed change in ocean surface temperatures. It is estimated that the ocean surface is now about approximately 0.7 °C higher than between the 19th century and year 2000. Since then, the surface temperature has been increasing at a rate of almost 0.2 °C per decade [6]. At this rate the temperature would have risen by over a median of 2 °C globally by the end of this century. There are even some models that predict a rise of almost 1.5 °C by the beginning of the year 2020 [7]. The effects of rising ocean temperatures do not only affect the ocean surface, but these higher temperatures propagate through the lower layers forming new thermoclines. However, since most of the published studies are for the ocean surface, it is even more important to understand the effects of these phenomena in underwater environments, as this is where most of the underwater sensor networks would be deployed and much of acoustically communicating marine mammals are also found here.

These rapid changes in the ocean make it important to characterize the expected effects of climate change on underwater acoustic communication. In this paper we present a study conducted to understand the effects of rising temperatures and increasing ocean acidity within the framework of global climate change and anthropogenic ocean acidification. A mathematical model suitable for the study is presented, followed by some numerical analysis. A discussion on the expected impact of the obtained results on digital

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communications and marine mammals follows along with some conclusions, which may be drawn from the study.

II. Mathematical Model

The ocean being a highly complex medium for the propagation of sound, due to inhomogeneities and random fluctuations, including effects of the rough seas and ocean bottom variances, warrants the need of a robust mathematical model that takes into account parameters like propagation loss, ambient noise, propagation delay and effects of temperature, acidity and depth, which can be used as a basis for evaluating acoustic communications.

a) Sound Speed: Though sound velocity in the ocean is normally assumed to be 1500 m/s, it is actually dependent on many parameters such as ambient temperature, salinity and acidity. Owing to the possibly rapidly changing conditions of the ocean, it is considered to be a stratified and range independent medium that varies only with depth. This assumption assists in creating a sound velocity profile.

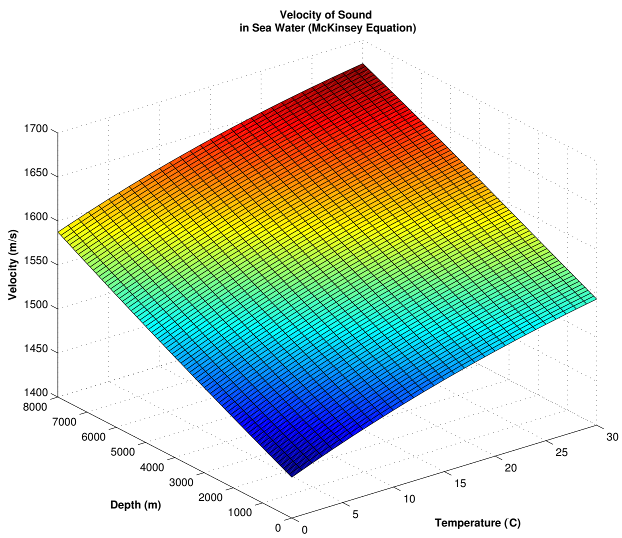


Figure 1. Speed of sound in ocean water relative to depth and water temperature (Salinity = 35 ppt)

The speed of sound in water has been a focus of analysis by many mathematical models. After a thorough discussion of the factors effecting the speed of sound in water, the authors of [8] present an equation, which calculates the speed of sound in water with an error in the speed estimate in the range of approximately 0.070 m/s.

$$\begin{aligned} v &= 1448.96 + 4.591T - 5.304 \cdot 10^{-2}T^2 \\ &+2.374 \cdot 10^{-4}T^3 + 1.340(S-35) \\ &+1.630 \cdot 10^{-2}D + 1.675 \cdot 10^{-7} \cdot D^2 \\ &-1.025 \cdot 10^{-2} \cdot T \cdot (S-35) \\ &-7.139 \cdot 10^{-13} \cdot T \cdot D^3 \qquad (1) \end{aligned}$$

Here, T is the temperature in °C, D is the depth in meters and S is the salinity in parts per trillion.

Table I
Values for representing types of geometrical spreading via the geometrical spreading coefficient k

	Spherical	Cylindrical	Practical
k	2	1	1.5

Using Equation 1 a graph of the speed of sound in water, with varying depth and temperature, is plotted in Figure 1. It is clear from Figure 1 that the speed of sound in water is not a constant of 1500 m/s but rather varies within a range of $1400 \leq v \leq 1700$. Furthermore, Figure 1 also makes it clear that the speed of sound increases with depth and also with ambient temperature; while the vertical gradient of sound velocity appears to be much larger compared to the horizontal gradient.

b) Propagation Loss: A transmitted underwater acoustic signal reduces in overall strength over distance due to a host of factors governing the sound propagation factors in ocean. This decrease of acoustic intensity between the source and receiver, termed propagation loss, is composed majorly of three aspects, namely, geometrical spreading, attenuation and the anomaly of propagation. While it is nearly impossible to model the anomaly of propagation, geometrical spreading deals with the signal losses that occur due to focusing and de-focusing effects caused by spreading of acoustic waves in the ocean water as a result of refraction and reflection; and can be modeled mathematically. Attenuation is the signal loss associated with frequency dependent absorption in the underwater channel and multiple models exist to estimate the signal attenuation in ocean water. The overall propagation loss that occurs over a transmission range l for a signal frequency f can be obtained from:

$$10 \log A(l,f) = k \cdot 10 \log l + l \cdot 10 \log \alpha \qquad (2)$$

where α is the absorption coefficient in dB/km, which can be obtained from models specifically characterizing it, and k represents the geometrical spreading factor obtained from Table I.

Attenuation by absorption occurs due to the conversion of acoustic energy within sea-water into heat. It is, as such, important to choose an absorption coefficient which characterizes the effect of ocean chemistry in order to use Equation 2 to study the impact of climate change and ocean acidification on acoustic communication. This process of attenuation of absorption is frequency dependent since at higher frequencies more energy is absorbed. There are several equations describing the processes of acoustic absorption in seawater which have laid the foundation for current knowledge.

The Ainslie & McColm equation, shown below, provides the attenuation coefficient α in dB/km, with a focus on the depth and ambient temperature, salinity and acidity of the ocean:

$$\begin{aligned} \alpha &= 0.106 \frac{f_1 f^2}{f_1^2 + f^2} e^{\frac{pH-8}{0.56}} \\ &+0.52 \left(1 + \frac{T}{43}\right) \left(\frac{S}{35}\right) \frac{f_2 f^2}{f_2^2 + f^2} e^{\frac{-D}{6}} \\ &+4.9 \times 10^{-4} f^2 e^{-\left(\frac{T}{27} + \frac{D}{17}\right)} \qquad (3) \end{aligned}$$

Table II
AINSLIE & MCCOLM MODEL'S COEFFICIENTS

$$f_1 = 0.78\sqrt{\frac{S}{35}}e^{\frac{T}{26}}$$
$$f_2 = 42e^{\frac{T}{17}}$$

The coefficients for Equation 3 may be obtained from Table II; where pH is the acidity of water, S is the salinity in parts per trillion, T is the temperature in °C and D is the depth in meters.

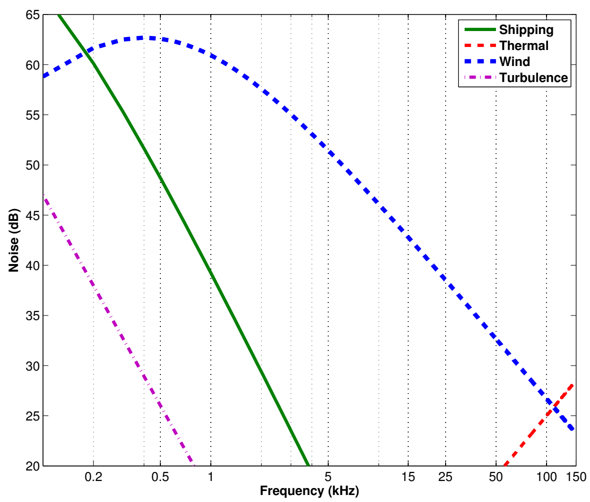


Figure 2. Dominance of different ambient noise types in the ocean.

c) Ambient Noise: Studying the effects of changing climate and acidity on the ambient noise is important, because not only does this effect the quality and dependability of communications, but has a direct effect on the livability environment for marine life as well. Ambient noise in the ocean can be described as Gaussian and having a continuous power spectral density (p.s.d.). The four most prominent sources for ambient noise are the turbulence, shipping, wind driven waves and thermal noise. The p.s.d. in dB re μPa per Hz for each of these is given by the formulae [9] shown below:

$$10 \log N_t(f) = 17 - 30 \log f \tag{4}$$

$$10 \log N_s(f) = 40 + 20(s - 0.5) + 26 \log f - 60 \log(f + 0.03) \tag{5}$$

$$10 \log N_w(f) = 50 + 7.5w^{\frac{1}{2}} + 20 \log f - 40 \log(f + 0.4) \tag{6}$$

$$10 \log N_{th}(f) = -15 + 20 \log f \tag{7}$$

Ambient noise in the ocean is colored and hence different factors have pronounced effects in specific frequency ranges. In the noise model equations utilized for this study the colored effect of noise is represented by N_t as the turbulence noise, N_s as the shipping noise (with s as the shipping factor which lies between 0 and 1), N_w as the wind driven wave noise (with w as the wind speed in m/s) and N_{th} as the thermal noise.

The effect of each of these types of noise is plotted in Figure 2. From this figure it is clear that turbulence noise influences only the low frequency region and similarly noise caused by distant shipping is dominant in the lower frequencies as well. Wind driven waves produce noise which creates far more noise than other ambient elements, until thermal noise becomes dominant for $f > 100$ kHz.

While ambient noise does not change directly as a result of increasing temperature and salinity, the changes in other aspects of the channel could lead to higher noise. Furthermore, since channel characteristics, such as bandwidth, capacity and signal-to-noise ratio (SNR) depend upon ambient noise, it is important to be able to model this accurately.

III. RESULTS AND DISCUSSION

The mathematical model described in the previous section, to study the effects of changing climate and increasing acidification in the oceans, is useful to better understand the impact on digital communications and also marine life. While these effects do not become completely clear immediately, the consequences can be obtained after some analysis.

A direct relationship between salinity and ocean acidity has not yet been shown to exist, as such, the changes in ocean pH are unlikely to effect sound velocity. However, from Figure 1 it is already known that sound velocity in the water increases with rising temperatures. The impact of increasing sound velocity due to rising ocean temperatures, as a result, is most likely to impact digital communications more than marine mammals. The increasing temperatures would result in lowered propagation delay, which in turn, would reduce latency of digital networks.

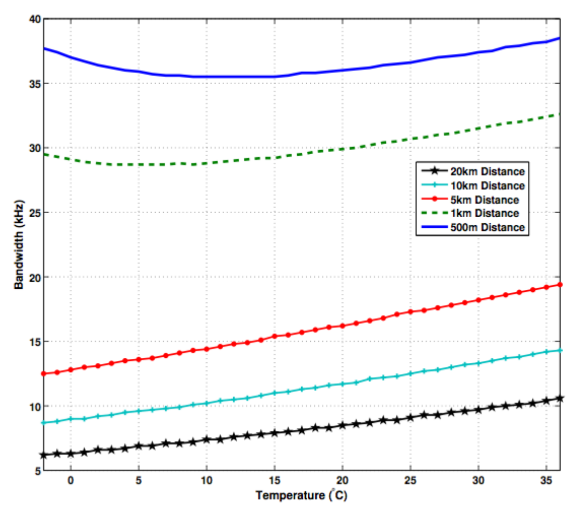
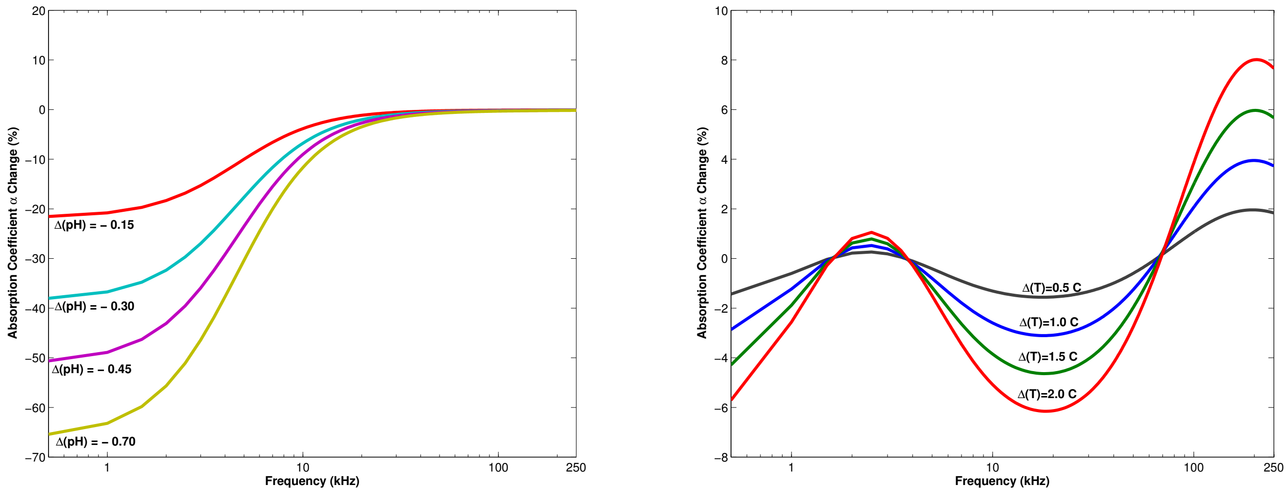


Figure 3. Effect of increasing temperature on the underwater acoustic channel bandwidth. (Transmission power of 120 db is used at a depth of 500m) [10]

It is already known that increasing temperature causes the available channel bandwidth to increase as well [10]. The effects of temperature on bandwidth can be seen in Figure 3. From the figure it becomes clear that the rising temperatures caused by climate change would lead to bandwidth in short range communications to reduce, however, long range



(a) (b)

Figure 4. The percentage change in sound attenuation by absorption in seawater (a) as per changing pH predicted by anthropogenic ocean acidification models and (b) as per the temperature increases predicted by climate change models; temperature changes are relative to year 2000 level. Base parameters used to compare against: Salinity=35 ppt, Temperature=12°C, pH=8.1 and Depth=100m.

communications would benefit. Bandwidth and capacity share a close relationship, as a result of which, this increasing bandwidth for long range communications would also lead to increased capacity, and thereby increased overall bit-rates in underwater acoustic communication.

Thus far, it seems that climate change would improve the plight of digital communications in the underwater acoustic channel but not greatly effect marine mammal communications since they are not highly dependent upon parameters like bandwidth and propagation delay. However, to obtain a clear picture, it is also necessary to understand the effects of anthropogenic ocean acidification, which is closely related to climate change.

As shown by Equation 3, attenuation by absorption is directly influenced by a change in ocean acidity. As such, it is logical to conclude that anthropogenic acidification is also leading to a change in the absorption based attenuation and propagation loss. Figure 4 (a) shows the amount of change that can be expected if the pH levels reduce by up to 0.7, as claimed by some models [3], [4]. Though the frequencies above 10 kHz are expected to experience an absorption attenuation only about 10% greater, the lower frequencies may experience attenuation that is almost up to 65% higher than those experienced in regular oceanic geochemical conditions.

Most acoustic modems used for digital communication lie within the 10-50 kHz transmission range [11] and as such, will experience a transmission loss which could be up to 20% higher. However, the effect does not stop only there, since even the SNR for a transmission over distance l using a the frequency f is indirectly related to the attenuation coefficient, as shown by the equation below:

$$SNR(l,f) = \frac{P}{A(l,f)N(f)\Delta f} \tag{8}$$

Here, P is the transmission signal power, $A(l,f)$ is obtained from Equation 2, which depends on attenuation by absorption, $N(f)$ is obtained from a summation of the result of Equations 4, 5, 6 and 7, and Δf is the bandwidth. Upon close inspection of Equation 8 it could be said that there exists an attenuation-noise factor, $A(l,f)N(f)$, which is inversely proportional to the SNR. Since the attenuation-noise factor is dependent on the absorption coefficient, it can be deduced that SNR will grow inversely to the attenuation-noise factor. Consequently, in the context of digital communications, it could also be said that the anthropogenic ocean acidification could lead to a SNR increase of up to about 20%.

The bit-error rate (BER) experienced in digital communication, while a property of the modulation scheme chosen, can also be shown to be effected by this change in the absorption coefficient. Assuming BPSK modulation, the BER can be obtained from the following equation:

$$p_{b,PSK} = \text{erfc}\left(\sqrt{\frac{E_b}{N_o}}\sin\left(\frac{\pi}{2}\right)\right) \tag{9}$$

where,

$$\frac{E_b}{N_o} = SNR(l,f)\frac{B(l)}{C(l)} \tag{10}$$

$SNR(l,f)$ can be obtained from Equation 8, $B(l)$ is the transmission bandwidth over distance l and $C(l)$ is the capacity, which can be obtained by using the Shannon theorem [10]. The dependence of BER on SNR, bandwidth and capacity, all of which are effected by ocean acidity, strongly indicates that the BER would rise with increasing acidity, however, the effect would not be as pronounced due to the form the BER function takes.

The change in the absorption coefficient due to the expected rise in temperature, as a result of the global climate change, within this century is plotted in Figure 4 (b). Similar to the effects of anthropogenic ocean acidification, oceanic warming will also lead to a general increase in SNR, BER and the signal attenuation. However, for digital acoustic communications, this change is not as severe and is expected to be within a maximum of 6% for the worst-case scenario.

While it is useful to understand the effects of acidity and temperature change separately, the combined effects also need to be analyzed since the ocean acidification phenomenon and global climate change are both a result of anthropogenic carbon dioxide production. Figure 5 plots the combined effects of worst-case ocean acidification and temperature rise at different depths, while still following the observed thermocline behavior of temperature in different layers of the ocean. It becomes clear from the figure that within the frequency range of acoustic modems used for digital communication, the worst-case scenario would be an approximately 15% increase in absorption influenced attenuation.

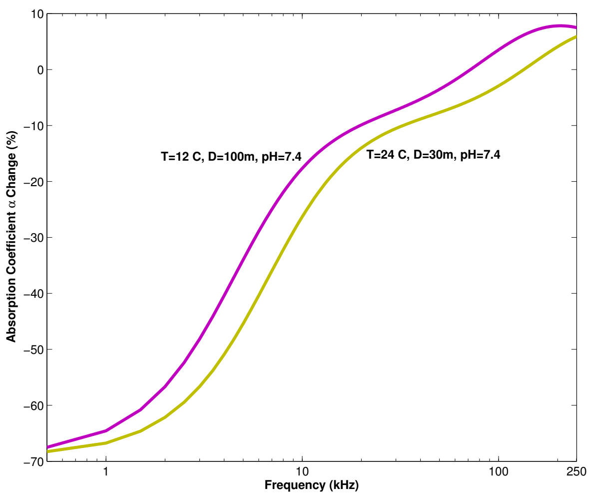


Figure 5. Combined effects of oceanic warming and anthropogenic ocean acidification on the absorption coefficient. The figure shows the worst case scenario at multiple depths, while following the general shape of a thermocline and halocline. The resulting temperature change of 12°C in the figure is a result of the depth change, following the thermocline model provided in [6].

Figure 6 shows a plot of the change induced in the attenuation-noise factor as a result of the combination of ocean acidification and temperature rise. Two cases are plotted, the worst-case model and a median case. However, from both these models it becomes clear that changing climate will lead to an increase in the SNR of digital communication by up to 10-15%. Consequently, this will also cause an increase in the BER and transmission power requirements.

The results discussed so far show that even though digital underwater acoustic communications will make some gains in the form of lower latency and higher bandwidth, these gains are more than negated due to the high levels of SNR, BER and transmission power requirements which would creep up as a result of the increased attenuation by absorption. These changes in the operating environment would require underwater communication systems to be designed in a robust way to overcome the increasing challenges the aquatic medium appears to be posing in the face of climate change and

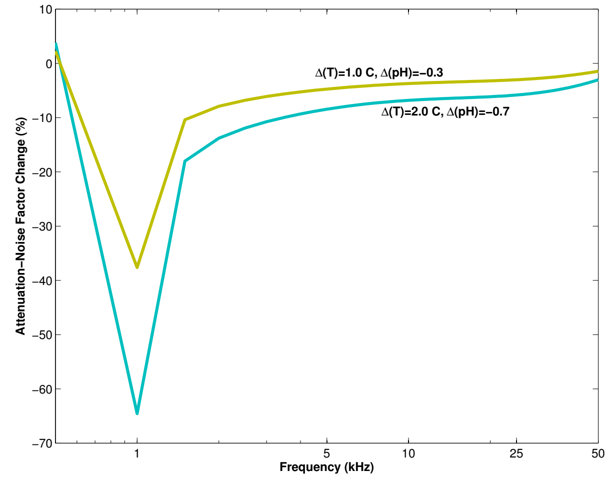


Figure 6. Effect of climate change and anthropogenic ocean acidification on the attenuation-noise factor (inversely proportional to SNR) as per a median and worst-case climate model.

anthropogenic acidification.

The effects of ocean acidification and climate change are not only limited to man-made acoustic communication systems, but also extend to marine mammals. Though marine mammals communicate using different tonal frequencies depending upon the oceanic region of the world, their general communication range is limited to frequencies of up to 150 Hz [12]. The most immediate result noticeable from Figures 4 and 5 is the high degree of reduction in attenuation by absorption within this frequency range, which obviously points towards significant increase in the ambient noise.

The decrease in attenuation by absorption, as effecting marine mammals, is expected to lie within a range of 20% (best case) to 70% (worst case). Traditionally, such low frequencies are dominated by ambient noise resultant from distant shipping and turbulence, the effects of which are not extremely steep. However, such high reductions in ambient noise will undoubtedly cause the oceans to get significantly noisier, thereby making them a biologically dangerous environment for aquatic mammals and also causing disruptions in their ability to use the underwater acoustic channel for communication. The results shown in the figures here, however, are limited to the shallow water range of about 300-500m. The effects of temperature increase and acidification are expected to be more limited in the deeper oceanic layers, where most of the aquatic mammals spend majority of their time, and as such, for now the effects appear to remain limited.

The authors of [12] present data suggesting that since 1960, blue whale song in the North-East Pacific ocean has reduced in tonal frequency from about 65 Hz to 45 Hz; this represents a nearly 30% decline. The results from their study shows that this rate of decline is not only limited to a specific section of the ocean, but this phenomenon can be observed globally across different types of whale-song. Since the whale-song data from the North-East Pacific ocean is the

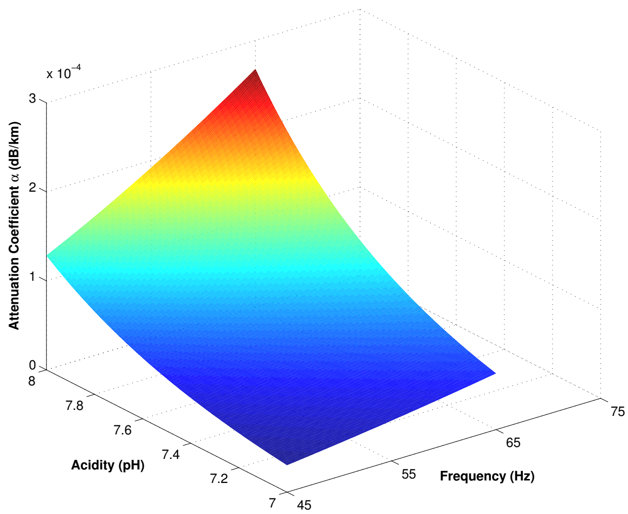


Figure 7. The impact of decreasing tonal frequencies on whale-song as coupled with the anticipated decrease in ocean acidity as a result of anthropogenic carbon. Blue whale tonal frequency data from the North-East Pacific ocean, between 1960-2010, was used along with the worst case $\Delta(pH) = -0.7$.

most complete, a plot of the attenuation coefficient against the observed frequencies and expected ocean acidity decline was made using this data. The results can be seen in Figure 7.

The result in Figure 7 shows that combining the predicted rate of shallow water acidity change with the observed frequencies, a nearly 30% decline in the attenuation coefficient can be obtained. As such, it is likely, that ocean acidification is a major contributor towards the observed decline in blue whale calls. However, it is interesting to note that at these low frequencies and attenuation factors, the ambient noise is likely to be more dominant as well. As such, other hitherto unknown external factors are undoubtedly contributing to the change in marine mammal acoustics.

IV. Conclusion

A mathematical model suitable for evaluating the effects of climate change and anthropogenic ocean acidification was presented in this paper. A numerical analysis of the model, using climate change and ocean acidification predictions, indicates that while there are some advantages like lower propagation delay for digital networks, these are offset by the high amount of rising SNR, BER and transmission power requirements to counter their effects. In some cases, up to 20% worse than existing conditions.

As a result of the sharp decline in attenuation by absorption, as a consequence of temperature and acidity increase, the ambient noise levels are expected to increase sharply in the shallow ocean layers (up to 500m). Effects of these phenomena will be much lesser in the deeper layers since the temperature and acidity is expected to rise slowly within them. However, the high ambient noise levels should be expected to impact marine mammal life in the shallow water layers significantly as they increase along with the changing climate and geochemical conditions. The up to 70% decline in attenuation by absorption within the frequency range of marine mammals can lead to significantly increased effect of ambient noise.

An initial effect of anthropogenic ocean acidification might already be visible through the 30% tonal frequency decline observed in blue whale song. This 30% decline can also be corroborated by ocean acidification models, as a result of the decreasing attenuation by absorption.

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