Is the ocean really getting louder? Whale population sound contribution to the marine acoustic environment prior to their extirpation by industrialized whaling.

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ABSTRACT

In 1975 Donald Ross identified a long-term trend that low frequency sound levels in deepwater open-ocean environments had increased by 0.55dB/year between 1958 and 1975 due to anthropogenic noise sources (Ross 1976). This trend in ocean ambient noise levels had largely been a product of the expansion of global shipping and has yielded an increase in the ambient noise floor of the ocean that is anywhere from 6dB to 12dB higher than what it was in 1958 (depending on location). What became known as the "Ross Prediction" did not incorporate other anthropogenic sources of noise such as navigation and communication signals, noise from offshore fossil fuel exploration and extraction, and the noises from other marine industrial enterprises. There is a concern that the increase in anthropogenic noise is masking biologically significant sounds, although the evidence for this is still scarce and somewhat speculative. Meanwhile perhaps 90 percent of the biomass of complex vertebrates has been removed from the ocean since 1850 due to industrialized whaling and fishing operations. (Meyers and Worm 2003)

This paper examines whether the ocean noise levels may have been significantly higher in 1800 than in the 1958 baseline year of the "Ross Prediction" due to baleen whale vocalizations and other biological sources of sound.

I. Introduction

Ocean ambient noise has been increasing continuously since the industrialization of global shipping (Andrew *et al.*, 2002; McDonald *et al.*, 2006) and expansion in offshore fossil fuel exploration and production. There is both concern and evidence that this noise is inducing stress (Rolland *et al*., 2012) and compromising communication channels of marine mammals (Parks *et al.*, 2010). The bulk of this increase in anthropogenic noise was due to the mechanization of global shipping and the industrialization of marine extraction industries. This has occurred after the end of WWII (from 1945) through to the final years of industrialized whaling and the global moratorium on commercial whaling in 1982. While the commercial viability of whaling began diminishing as various species became "commercially extinct," as early as 1915 highly industrialized and illicit whaling in the 1960's accelerated the demise of many species down to population levels that were commercially unviable (Clapham and Baker 2002). The depletions were significant enough to bring the industry-coordinated International Whaling Commission (1946[1]) as whale populations could no longer support a commercial industry (Mackintosh 1965).

It has been estimated that hundreds of thousands to millions of baleen whales and sperm whales have been harvested since the beginning of commercial whaling. While some populations seem to have recovered (minke and sperm whales), others whales have become functionally extinct (e.g. Eastern North Atlantic right whale, Best et. al 2001), or

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[1] International Convention for the Regulation of Whaling, with Schedule of Whaling Regulations, 2 December 1946, 62 Stat. 1716, 161 UNTS 72.

the current populations are only a fraction of their pre-commercial whaling populations (Western North Atlantic right whale, blue whale) (Clapham et.al. 1999)

Whaling can be divided into two technological eras; pre-industrial, when whalers pursued whales in sailing ships, chased them in oar-powered dories, and killed them with hand-thrown harpoons; and post-industrial, when pursuit vessels were motorized and charge-fired harpoons with explosive points were utilized (Mackintosh 1965). Post-industrial whaling technologies not only exponentially increased the catch-rates, they also allowed the harvesting of larger and faster whales. In the beginning of commercial whaling the dominant species were right, bowhead, humpback, gray, and sperm whales (Townsend 1935). Post-industrial whaling technologies allowed for the pursuit of the larger rorquals such as blue, sei, and fin whales.

All of these commercially exploited whales vocalize to some degree. The amplitude of their vocalizations range from 128 – 192 dB re: 1µPa@1m [ref. 2] with the majority of sounds occurring in the range of 165–190 dB. With the exception of foraging clicks and buzzes of the sperm whales, and song components of the humpbacks and bowheads, the frequency band for most of these sounds are < 500 Hz (Richardson *et al.*, 1995). Given the quantity of animals harvested, the evidence presented herein suggests that whale vocalizations were the one of the dominant low-frequency (< 500 Hz) noise sources in the ocean acoustic environment prior to their extirpation.

A majority of commercial shipping noise energy also falls in the frequency band <500 Hz, with source levels in the range of 160–220 dB_{RMS}. Over the course of the last half

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[2] 1µPa@1m - reference used as "0dB" hereinafter unless otherwise noted.

century the global shipping fleet expanded greatly; from ~30,000 vessels (~85 million gross tons) in 1950 to over 85,000 vessels (~525 million gross tons) in 1998 (NRC 2003). Incidental noise generated by ships contributes significantly to low-frequency sound levels in the ocean (Richardson *et al.*, 1995), accounting for as much as 10 dB – 12dB 1μPa/Hz increase in noise below 100 Hz by 2004 over the noise levels in 1966 (MacDonald *et al.*, 2006).

The expansion of global commercial shipping was concurrent to the decline of industrial whaling so that any ocean ambient noise measurements taken since the mid 1950's would have taken place after the greater part of the decline in whale populations. For example reported annual kill rates of blue whales from 1930 – 1940 was 20,000 – 30,000 per year, until WWII when the blue whale populations were not high enough to support commercial harvesting. While WWII halted commercial whaling for a few years, 20,000 total annual whale kills reported from 1946-1962 (excluding blue whales), which declined by 1964 to significantly limit all commercial whaling (Mackintosh, 1965).

The intent of this work was to model some of the possible scenarios in the sound power densities produced by whales prior to their large-scale extirpation due to industrial whaling.

II. Discussion

The noise levels fall under the following three categories:

- Natural ambient noise due to non-biological factors
- Natural ambient noise due to biological factors

- Ambient noise due to anthropogenic factors

All of these categories will have regional variability due regional dynamic conditions.

We can assume that the natural ambient noise due to non-biological factors has remained relatively constant since the ocean contained complex life forms. Any variability in non-biological noise levels would be due to due to weather conditions (storms, ice dynamics) or regional geological instability. Variability in noise due to biological factors will include diel and seasonal variability in shorter time frames, but as indicated herein, decadal or centennial variability will be due to variability in population densities over longer time frames.

Ambient noise due to anthropogenic factors will have regional variability due to proximity to population centers and industrial activity, and in terms of transportation noise, proximity to the transportation trajectory.

in the ocean are dynamic and dependent on location, season,

Natural ambient noise due to non-biological factors

The ocean is not a particularly quiet environment. The mechanical sounds of wind, rain, lightning, waves, surface chop, currents, earthquakes, and in polar regions the sounds of ice breaking, colliding, and scouring can produce both periodic and chronic noise some of which may exceed the phonation levels of marine animals. For example heavy precipitation can increase the noise in the 1kHz – 10kHz band to 83 dB re 1 μPa (Heindsman *et.al.*1955, Urick, 1967); occasional earthquakes can be very loud;

McCauley *et. al.* (2000) cites a level of 272dB re: 1 µPa-m peak,[3] and Urick (1967) has indicated 120dB above 1µPa of continuous noise below 1Hz due to microseisms. The constant shifting of the earth crust and mantle and suggests that the importance of this source of noise extends up into the 10Hz – 100Hz range in areas of low shipping traffic.

We can assume that with the exceptions of the occasional cataclysmic geological events that the mechanical sounds in the ocean have remained within a certain range of variability since before multi-cellular life appeared in the ocean. Wenz (1962) presents an array of ambient noise levels resulting from various sea states and finds that both shallow and deep water ambient noise peaks in the 100Hz to 500Hz band varies between 38 – 58 dB re .0002 dyne/cm^2/Hz and then drops off at 5 – 8dB per octave. This equates to 64 – 84 dB re 1 µPa/Hz depending on sea state (a conversion factor of +26dB will be used for Wenz 1962 hereinafter[4]).

Measurements referred to in Wenz (1962) were taken between 1945 and 1962 which crosses over the nadir of commercial whale populations and the lowest levels of commercial transportation noise (due to restricted merchant shipping during World War II) and then the subsequent rise in propeller-driven global maritime trade. The conclusion and resulting chart from Wenz (1962) indicate that shipping traffic noise was a dominant contributor of noise between 10Hz and 100Hz when these measurements were collated.

[3] This metric reference is a bit ambiguous due to the spatial dimension component of "m" for a sound without a point source, and "peak" not being correlated to crest factor or RMS value.

[4] .0002 dyne/cm^2 = 20µPa → $20\log_{10}$ 20µPa=26dB (sound pressure level)

Wenz (1962) also indicates that geo-seismic activity may produce levels of 103dB – 155dB re: 1 µPa which would constitute one of the loudest occasional sounds in the ocean. Richardson et. al. (1995) mentions the noise the deformation of land-fast spring ice peaking at 95dB re:1 μPa^2/Hz and Buck and Wilson (1986) measured sea noise from and active ridge on sea ice generating 120dB at 10 Hz and 105 dB at 250 Hz (re:1μPa^2/Hz).

R.D. Hill (1986) calculated that the broad band source level noise from a particular lightning strike was 260.5dB re:1µPa. which with the exception of large volcanic eruptions may be the loudest common noise in the sea. Hundreds of thousands of lightning strikes hit the planet each day, so those that do strike the ocean may be a significant contributor to the ocean ambient noise level although this is not reflected in the Wenz model. While a 260 dB re 1 µPa source level is loud enough to be considered damaging to the hearing organs of marine animals, the duration of this peak level may only be in the order of a few tens of micro-seconds, significantly diminishing the Sound Exposure Level (SEL = dB re 1 $\mu Pa^2 \cdot s$).

A propagation model for lightning also complicates the ambient noise contribution of lightening because the coupling of lightning to the water would likely include attenuation due to a multi-phase interface (gas, steam, and water), transmission loss due to sea surface conditions, and attenuation artifacts of the Lloyd mirror effect. Indeed R.D. Hill (1986) suggests that the noise contribution of lightning being between 109dB and 146.7 dB re: 1 µPa which is in line with other sea state and weather induced noises. Arnold *et. al.* (1984) substantiates these ranges in noting that noise from lightning strikes was “25 dB above the ambient ocean noises[5]" and estimated that the measured strike was 60km distant. Assuming that the ambient noise of the ocean was 100dB, the noise at his measuring point was 125dB, and at 60km was 47.8 dB [ref.6] higher at the source, giving a source level of 172.8 dB.

It may be determined from the foregoing that in certain areas of the ocean at certain times the ambient noise levels can be as high as 121 dB due to weather-driven sea state, and as high as 155 dB due to seismic activity. Additionally lightning may cause local spikes as high as 260 dB, although source level spikes as high as 177dB are more consistent with measured lightning (from Arnold 1984) rather than modeled (from Hill 1986).

Ambient noise due to anthropogenic sources

The acoustical impacts of human engagement with the marine environment has become globally significant since fossil fuel driven ships and boats began plying the waves. This is implied herein as well by the fossil-fueled extirpation of the great whales – diminishing the most significant source of low frequency biological noise in the sea facilitated by the mechanization of the whaling industry (Mackintosh, 1965). But the acoustical artifacts of fossil fuel are also represented in the noises that mechanized human enterprise have added to the ocean soundscape. Of enduring concern is the expanding reach of shipping noise – primarily caused by propeller cavitation, but also in hull-coupled mechanical noises and hull friction (Ross, 1976).

[5] Arnold did not state the ambient noise level in this paper.
[6] 10dB Log 60km re: 1m = 47.8dB for cylindrical propagation

Since the 1990's scientists and the public have been increasingly concerned with the noises of military and other active sonar (D'Amico and Pittenger, 2009), seismic airgun surveys in search of offshore fossil fuel (Gordon, J., et al. 2004), and the impacts of pile driving on fish (McGee, 2005, Abbott and Reyff, 2005) and marine mammals (Kastelein et. al. 2013a, 2013b).

Additional anthropogenic noise sources are also modifying the marine soundscape, including underwater acoustic communication systems, acoustical technologies used for various ocean observing systems, seafloor minerals extraction operations, and seafloor processing for fossil fuel extraction.

Shipping noise

The anthropogenic sources of noise referenced in Donald Ross' "prediction" (Ross 1976) was focused on shipping noise and it's increase over time due to the expansion of global shipping trade. While Wenz (1962) examined "ambient noise" largely in terms of sea states and other hydrodynamic sources of ocean noise, he also included ship noise contribution to ambient noise but made the distinction between ship noise "from one or more ships at close range"[7] (which was excluded from "ambient noise") and "traffic noise …resulting from the combined effect of all ship traffic" which was considered ambient noise because it was not "obvious" as individual noise sources.

It should be noted here that Wenz models noise contributions from ship traffic by way of data obtained from Dow et. al (1945) which include propagation characteristics and band

[7] [which.] "… may be identified by short term variations in ambient noise characteristics such as the temporary appearance of narrow band components and rapid rise and fall in noise level. Ship noise is usually obvious and therefore generally can be and is deleted from ambient noise data."

attenuation correlated to distance from the source without specifying the location of any of the measurements. This would suggest that the “Wenz Curves” were modeled rather than empirical, and used data at the early age of fossil-fuel driven international trans-oceanic shipping when there were significantly fewer ships at sea.

Nonetheless it is clear that global ambient noise contribution from commercial shipping has increased in the past 50 years. And while some areas have seen the 2 – 3.5 dB per decade increases in noise found in the northern hemisphere (MacDonald et.al 2006) other areas have not seen these increases due to being away from major global trade routes (Cato 1976). Clark et.al. (2009) illustrate this variability through audiograms of the marine ambient environment in non-industrialized Gulf of California where noise level in the 20-30Hz range occasionally exceed 110dBre: 1µPa, and is mostly below 80 dB, and the Mediterranean Sea which is rarely below 95dB between 20 Hz and 120 Hz, and often above 110dB. Shipping lanes are increasingly expanding throughout the globe, but are more densely packed in certain areas such as the North Pacific and North Atlantic following the tracks of commerce, leaving the South Pacific and South Atlantic and the southern Indian Ocean relatively empty.

Seismic Surveys using towed airgun arrays.

Not included in either the “Ross Prediction” or the Wenz model are the increasing preponderance of seismic airgun surveys – a technology used to explore coastal and outer continental shelf (OCS) areas for hydrocarbon deposits. These operations involve towing arrays of pneumatic devices that release impulses of pressurized air into the surrounding environment. These pulses are driven at a cycle rate of 10 – 17 seconds and are tailored to deliver signals below 500 Hz. Depending on the size of the array the can be heard up 3000 km distant. (Nieukirk et. al 2004). Fossil fuel operations are expanding into ever deeper water throughout most areas of the globe, with the current exceptions of the eastern coast of North America, the western coast of North, Central, and South America and in the Antarctic.

With the dynamic growth of the marine geophysical survey industry there has yet to be an ocean-basins or global noise contribution assessment of this noise source, although regional assessments have been, and continue to take place (Nieukirk et. al 2004, Guerra et.al. 2011, Roth et.al 2012). These assessments indicate that seismic airgun surveys are increasingly becoming a recognizable feature of the ocean soundscape due to widespread expansion of deepwater fossil fuel exploration and production.

Seafloor Processing

The expansion of deepwater fossil fuel exploration and production includes extraction and seafloor processing technologies. Seafloor mounted separators, multi-stage and multi-phase pumps, valve trees and manifolds. Depending on the characteristics of the deposits these can be operating under very high pressure. Pressures up to 150,000 kPa (20,000 psi) are not uncommon. Multiphase substance (solids, gas, liquids) in motion under these pressures is likely to generate some noise, but these noises have yet to be assessed in terms of their contribution to the global or regional ocean soundscape.

Other sources of anthropogenic noise

The topic of this paper concerns anthropogenic and biological sources of low frequency noise contribution qualified as “ambient” and quantified as the >50km minimum distance to the source. Nonetheless localized (<15km) mid and high frequency sound sources are increasingly becoming part of the regional ocean soundscapes. It is not in the scope of this paper to analyze the soundscape artifacts of these sources, but due to the proliferation of new mid frequency (1-10kHz) and high-frequency (>10kHz) acoustical signals for reconnaissance, machine control, monitoring, and communications these higher frequencies are changing the acoustical profiles in various areas of the ocean. Due to the propagation characteristics of sound in the ocean these mid and high frequency sounds typically attenuate after 10-15km. It could come to pass in that expanded networks of communications equipment, current profilers, and acoustical monitoring that the proliferation of these higher frequency sources will become an ubiquitous feature of coastal underwater soundscapes.

Ambient noise due to biological factors

As living organisms evolved from the first motile prokaryotes became more complex the sound of their motion, and later the sounds of their vocalizations and communication signals would become an increasingly more pronounced factor in the marine ambient soundscape. While there have been mass extinctions in the past, animal densities in our own age have been high enough in the recent past to be a significant factor in natural soundscapes.

In terms of bioacoustic precedents, the bioacoustic environment of the pre-industrial whaling ocean could be correlated to the animal sounds in any biologically diverse and well-populated habitat wherein the riot of birdcalls, the stridulation of insects, and mammal vocalizations are the dominant noise contributors to the soundscape

By way of examples: Before the eradication of the passenger pigeon James Audubon estimated that observing over three days more than 300 million birds *per hour* passed overhead. Until their slaughter in the 1860's over 60 million buffalo once roamed the central plains of the North American continent, and as late as the early 20th century west coast fishermen noted that great schools of tuna miles across would churn up the sea surface for days as they migrated past California's Channel Islands. The historic densities of wild animals are most often spoken of in visual terms, but skies blackened by billions of birds would also generate quite a lot of noise form their vocalizations and beating wings; and just the turbulence from large schools of large tuna would likely be as loud as or louder than even the most tempestuous sea state – or even the cavitation noise from the propellers of numerous ships.

Meyers and Worm (2003) suggests that in the past 100 years that as much as 90% of the top predators have been fished from the ocean. While the paper does not specifically identify known vocalizing species such as the Grunts (*Pomadasyidae*) or Drums (*Sciaenidae*), it stands to reason that industrial fishing has had equivalent impacts on these commercially exploited species. According to Mann and Locascio (2006), contemporary aggregations of these vocalizing species can produce noise levels of 110-120 dB re; 1 µPa. While localized noise levels from these fish may not be significantly higher due to local distribution densities, larger aggregations over broader ranges would likely contribute to the overall ocean ambient noise levels.

Modeling the acoustical impacts of these depletions is beyond the scope of this paper, but it is clear from the forgoing that due to significant decreases in population densities of fish species which contribute to ambient marine noise either by vocalization or physical motion that the ocean ambient noise is now lower as a consequence of the depletions.

Given the comparable depletions of marine mammals during the industrialized commercial whaling period, it is certain that the noise contribution of marine mammals prior to industrialized exploitation was louder than their current contribution – consistent with the models presented herein, and possibly louder than in many locations than the current ambient noise of the ocean which now includes industrial noise.

Masking and acoustical niches

If the ocean ambient noise was louder prior to industrialized whaling than it is today it might be assumed that the concern for industrial noises masking biologically significant signals is over-stated, and that marine animals may have perceptual filters that allow them to discriminate biologically significant signals in a field of noise.

Filtering in the time domain allows discrimination of biologically significant signals in a field of noise (Miller et.al. 2004, Tougaad et.al 2004). Other discrimination techniques may exist as well, but marine animals have adapted to their acoustical habitat in ways that reflect biological interdependence through acoustical niches (Mossbridge, 1999). This includes selecting acoustical niches in the frequency domain (Narins, 2011) as well as in the time domain (Gerhardt and Huber, 2002). There may be some plasticity in a given species if they are pressured to adapt to habitat variability (Slabbekoorn, 2004) but the evolution of animals traces a long arc of responses to adaptive pressures all within biological and natural time frames.

There is evidence that some animals have adapted to the recent introduction of mechanized sounds into natural environments (Slabbekoorn and Peet, 2003, MacDonald et.al. 2009), but the signature of mechanized ocean noise interference from shipping is broad-band, pervasive, and chronic, and more likely to mask across animal frequency and/or time domain filters throughout large areas of the ocean.

Sound quality considerations

While the preponderance of shipping noise falls below 500Hz (Wenz, 1962) the introduction of marine acoustic communication systems and other mechanized processes may saturate other biological communication channels in a more localized manner at higher frequencies and with signal types and characteristics (such as high-kurtosis digital communication signals) that are outside of signal types to which marine animals are able to adapt or habituate.

It is indeed the quality of recently introduced sounds that have not been brought into regulatory consideration. Current regulatory thresholds depend exclusively on exposure level alone[8] without considering that various sound types may have antagonistic or aversive impacts independent of amplitude (Halpern et.al 1986, Sukhbinder et.al 2008). Additionally marine acoustical niches in the time and/or frequency domain are predicated on the availability of an acoustical niche to occupy. Broad-band continuous noises

[8] c.f. “Draft Guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammals Acoustic Threshold Levels for Onset of Permanent and Temporary Threshold Shifts” 2013 National Oceanic and Atmospheric Administration. Currently in review as of June 2014.

characteristic of shipping noise and long-term seismic surveys mask these niches in both the time and frequency domain (Clark et.al. 2009).

And while the ocean can be noisy due to various biological and non-biological sources, all of these sources are temporally variable – either by diel, lunar, or seasonal cycles, or meteorological mechanisms.

Geographic variability

The ocean is not just one place. While the blanket statement is often heard that “the ocean is 10 times (10dB) louder than it was just 50 year ago” this is certainly the case in some locations, but not in others. Clark et.al. (2009) illustrate this variability through audiograms of the marine ambient environment in non-industrialized Gulf of California where noise level in the 20-30Hz range occasionally exceed 110dBre: 1μP, and is mostly below 80 dB, and the Mediterranean Sea which is rarely below 95dB between 20 Hz and 120 Hz, and often above 110dB. Shipping lanes are increasingly expanding throughout the globe, but are more densely packed in certain areas such as the North Pacific and North Atlantic following the tracks of commerce, leaving the South Pacific and South Atlantic relatively empty. Seismic Airgun surveys occurring on most continental coasts are not yet found on the Atlantic or Pacific Coasts of North America, the polar regions, or the Pacific Coast of South America. Various species of whales on the other hand can and have been be found throughout the oceans and depending on season and behavior can produce quite a din.

III. Results and conclusion

Given the range of uncertainties expressed in the Methods section, any results can only be considered approximations. Nonetheless they do provide a framework within which to evaluate the possible acoustical energy contribution from the vocalizations of the subject whales.

While there is not enough accurate, confirmed, and correlated data in the literature to derive an accurate model of pre-whaling biological noise levels in the ocean, we believe that the data calculations presented in Table III indicate that the once-abundant species of Mysticetes were a major contributor to basin-wide ocean noise levels in the 1800s and before. And while the overall ocean was likely louder in the early nineteenth century than it is now due to biological noise, it does not diminish the need to understand the impacts of introduced anthropogenic noise into the marine environment. It also highlights the need to understand if and what type of perceptual noise filters have evolved in marine animals. Greater understanding of this may allow ocean enterprises to tailor anthropogenic noise generation and mitigation practices to reflect pre-industrial noise sources and thus be more accommodating to the evolutionary adaptations of marine life.

IV. Methods

The determination of the noise contribution of whales into the ocean soundscape might reasonably involve determining the population densities of all whales at any given time, modeling the average noise contribution of the individuals of each species, adding them all together and distributing these individual “noise units” across the subject habitat and calculate the resulting noise density in the habitat. Implicit in this model is that unlike ships which continuously make noise while underway, whales only vocalize as one part of their complex behavioral repertoire, which may include periods of dense and loud group and individual vocalizations along with periods of quietude. A rough accommodation of this characteristic is included in the model.

Three variables in a field of uncertainties:

The three variables in this simple model are:

N = total number of subject whales

L_s = acoustical energy produced by each individual animal

δ = density of whales throughout the volume of the subject area

Pre-whaling and whaling period population counts (*N*)

Determining pre-whaling population densities of hunted whales should be as simple as taking the population of whales at the end of global commercial whaling, subtract the number of whale kills over the whaling era and factor in the "recruitment rate" of the various species (increase in population due to births, minus non-whaling death rate) over that same time.

$$N_i(t) = N_i(0)[(1 - \delta_i)e^{-r_i t} + \delta_i] \qquad \text{(Eq. 1)}$$

where $N_i(t)$ is the population at time t, $N_i(0)$ is the initial population before industrialized exploitation, and r_i is the initial rate of decline to δ_i, the fraction of the population that remains at equilibrium. The initial rate of decline in total population, or the fraction lost in the first year, is $(1 - \delta_i)(1 - e^{-r_i})$. We then combined all data using nonlinear mixed-effects models, where $r_i \sim N(\mu_r, \sigma_r^2)$ and $\log \delta_i \sim N(\mu_\delta, \sigma_\delta^2)$, to estimate a global mean and variance of r_i and δ_i (Davidian & Giltinan 1995).

Unfortunately, deriving an accurate count of pre-industrial whale population densities is fraught with uncertainties. This is primarily due to the fact that it has never been advantageous for whalers to accurately report their catches because they were taxed by their governments, and later regulated by the International Whaling Commission based on the size of their takes. This situation was aggravated by the expanse of the ocean wherein accurate counts depended greatly on self-monitoring, (Stocker 2007) and in which the error margins can vastly increase when there is an incentive to prevaricate (Clapham and Ivashchenko 2009).

As a consequence, whale kill claims typically vary from 5-30% of actual kills, thus for example in the early 1960's the Soviets had claimed taking only 2,710 Humpback whales when the actual number was closer to 48,000 (Clapham and Ivashchenko 2009). While the Soviet example was particularly egregious, the wide variability in pre-whaling population estimates points to a widespread practice of under-reporting kills.

The premise of this work is that with the exception of whale species with relatively high recruitment rates such as the minke (Ruegg et. al. 2010) and species that have been on an upward population trend such as the eastern Pacific gray whale (Alter et. al. 2007), pre-industrial populations of exploited species (blue, fin, bowhead, right, and humpback) were arguably ten times higher than their current populations (Roberts, 2007). So in our model $N_i(t)$ will be an open variable to test various scenarios including the aggregate of all whales in a given area, or the lower and higher estimates of a given species in a specific area.

It became clear in the course of this examination that due to the high kill rates inflicted on post-industrial whale populations, many of the modeling variables incorporating the finer points of "recruitment" and "percent of population that remained in equilibrium" were essentially made moot because the kill rate so far exceeded recruitment rate that equilibrium was not possible. In some cases, such as the southern hemisphere blue and fin whales, the "kill rate" served as the most reasonable proxy to determine pre-whaling populations. This is in light of the fact that current populations of these species could be less than 10% and as low as 5% of their historic populations (IWC 2007).

Vocalizing behavior

Accurate models of the net acoustical energy of individual whales were difficult to derive because of the paucity of geographically correlated data on the diel, seasonal, annual, and even gender-correlated vocalizing behaviors of the animals.

Uncertainties in vocalization models include:

1. Individual vs. group vocalizations: There is still much speculation about the distinctions between social, hunting, and navigation sounds of various species.
2. Seasonal-specific vocalizations: Seasonal variations in food supplies, breeding, and social opportunities effect vocalization.
3. Seasonal-specific distributions of animals in feeding, courting, breeding, and migrating behaviors.

4. Density-dependent habitat selection: When there was a higher density of individuals of any species there is no clear record of whether they aggregated in higher densities, or dispersed over wider areas.
5. Proximity to conspecifics and masking by non-specifics: Is vocalization amplitude modified as a consequence of proximity to other whales? Are whales subject to "the cocktail party effect"?
6. Paucity of data on vocalization depth: How deep were various signals produced and recorded and what are the distance/propagation characteristics of various signals as a consequence of where they were produced and recorded in the water column?
7. Lack of data on sexual dimorphic vocalizations: How do vocalizations for mate selection and advertisement of breeding fitness vary with species?
8. Recorded sound source data on whale vocalizations were from contemporary living animals and can only serve as a proxy for vocalization behaviors whales long dead. Did the impact of industrial whaling have any effect on whale vocalizing behavior?

Additionally we were only able to use vocalization data which included standardized source level (dB re: 1μPa@1m), typical call duration, and call density (calls per hour) to derive "ρ" ([duration * calls hr $^{-1}$]*3600 sec. $^{-1}$) (See Table I). As a consequence only certain representative species could be included into the model. The species for which we did have suitable data we did not account for seasonal variability in call densities. This is particularly the case with humpback and bowhead whales where "ρ" is a product of vocalizations associated with breeding seasons.

Density distribution of whales (δ)

Uncertainties in density and distribution also arise from the records. Commercial enterprises are not predisposed to announcing their productive fishing grounds. The maps in Townsend (1935) do highlight concentrations of takes. Some high-density take areas are correlated with regional upwelling and geographic features, while others seem more correlated to opportunities such as agreeable weather conditions and proximity to favorable ports.

To overcome some of this uncertainty we have chosen to look at ocean basins as a reverberant model (Ross, 1976):

$$L_n = L_s + 10\log\theta_e - 10\log\alpha_T H + 10\log\delta \qquad \text{(Eq. 2)}$$

Where: L_n = ambient sound pressure level

L_s = individual whale average source level

θ_e = a propagation factor reflecting the contribution of glancing rays to the reverberant field

α_T = attenuation by absorption and boundary reflection losses

H = average depth in kilometers

δ = density of whales throughout the model area in whales/km^2

This equation integrates the whale's net contributed noise from and unbounded center measuring point that assumes that the measurement is in the deep ocean and no single source is closer than 50 km to the measurement (below 500 Hz.).

This also assumes even distribution of whales throughout the subject area without consideration to oceanographic features. Similar statistical tools are employed to determine the probability of animal population densities in large areas by distributing the animals cited over a series of transects across the entire area or volume of the subject habitat (Rone *et al.*, 2010).

The following equation was used to run the various scenarios using the variables found in Table I and Table II. Results can be found in Table III.

$$L_n = L_s + 10log(\rho\theta_e\delta) - 10log(\alpha_T H) \qquad \text{(Eq. 3)}$$

Where:

L_n = ambient sound pressure level as a sum of the noise less the attenuation

dB_s = source level of the call

ρ = the "call density" ([call duration * calls hr^{-1}]3600 sec^{-1}) (See Table I)

L_s = the equivalent sound power of the calls (dB_s+10log ρ)

θ_e = 1/3 radian which is the reflected noise into the reverberant field [9]

α_T = 10log(distance from the source) - the attenuation factor for cylindrical propagation gradient in the far field (>50km per Eq. 2)

H = Average depth of the ocean (4 km)

δ = density of whales per km^2 (See Table II)

[9] This takes into account that only acoustical energy reflecting off of boundaries at fairly acute angles contributes to the reverberant field.

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Table I. Characteristic vocalizations of five species of Mysticetes. dB_s = source level of the call; ρ = "call density" ([call duration * calls hr^{-1}]/3600 sec).

Species	Area	dB_s	Duration (s)	Calls $(hr)^{-1}$	Freq. Hz	ρ	Source
Blue	N Pacific	184	16	43	16	0.191	Oleson *et al.* (2007)
Blue	NE Pacific	186	38	29.5	10-60	0.311	McDonald *et al.* (1995)
Blue	Chile	188	36.5	25	12.5-222	0.253	Cummings and Thompson (1971)
Bowhead	Arctic	177	66	16	25-900	0.293	Cummings and Holliday (1987)[10]
Humpback	Hawaii	159	828	4	100-5k	0.920	Fristrup *et al.* (2003)[11]
Fin	Global	186	1	270	17-25	0.075	Watkins *et al.* (1987)
Sei	NW Atlantic	156	1.4	37	34-82	0.014	Baumgartner *et al.* (2008)
Sei	NW Atlantic	156	1.4	500	34-82	0.194	Baumgartner *et al.* (2008)

[10] Sound recorded during April-May migrations associated with breeding behaviors and not representative of sound density during other seasons.

[11] These data were recorded during February-March associated with humpback whale breeding season and thus are representative of the elaborate male vocalizations characteristic of this species during this time of year and not representative of sound density during other seasons.

Table II. Variability in pre-whaling species population estimates.

Species	Area	Population Estimate	Source	δ(km2)-1[a]
Humpback	Global	115,000	Oceanus (1989)	0.000241
Humpback	Global	125,000	Fisheries Service (1991)	0.0002621
Humpback	N. Atlantic	20,000	Watkins (2003)	0.0004878
Humpback	N. Atlantic	240,000	Roman and Palumbi (2003)	0.0058537
Sperm [b]	Global	240,000	Oceanus (1989)	0.0005031
Sperm [b]	Global	1,100,000	Taylor *et al.*, (2008)	0.0023061
Sperm [b]	Global	1,110,000	Whitehead (2002)	0.002327
Sperm [b]	North Pacific	1,260,000	Rice (1989)	0.0151807
Bowhead	Arctic	30,000	Oceanus (1989)	0.0025
Bowhead	Arctic	50,000	Woodby and Botkin (1993)	0.0041667
Blue	Global	228,000	Oceanus (1989)	0.000478
Blue	Southern	350,000[c]	Clapham and Baker (2002)	0.0175
Fin	Southern	750,000[c]	Clapham and Baker (2002)	0.0375
Fin	North Atlantic	360,000	Roman and Palumbi (2003)	0.0087805
Fin	Global	548,000	Oceanus (1989)	0.0011488

[a] Region areas in km^2: Atlantic 82,000,000 N. Atlantic 41,000,000 Pacific 166,000,000 N. Pacific 83,000,000 Arctic 12,000,000 Indian 73,000,000 Southern 20,000,000, Global 477,000,000

[b] Sperm whale vocalizations are high frequency and highly directional thus would only contribute to their regional soundscape and not to noise <500Hz. They are included in the table for comparison, and because there are data on their vocalizations

[c] The number reported here is estimated kills in early 20th century, not the estimated population density.

Table III. Data calculations.

Species	dB_s	L_s(dB)	ρ	θ_e(Rad.)	α_T(dB)	H(km)	$\delta(km^2)^{-1}$	L_n(dB)
Humpbacks N. Atlantic	159	158.6	0.920	0.33	10	4	0.00049[a]	104.3
Humpbacks N. Atlantic	159	158.6	0.920	0.33	10	4	0.058[b]	104.3
Fin N. Atlantic	186	174.8	0.075	0.33	10	4	0.00211	116
Blue N. Pacific	184	176.8	0.191	0.33	10	4	0.000478[c]	115.6
Blue NE Pacific	186	180.9	0.311	0.33	10	4	0.000478[c]	121.9
Blue Southern	188	182.0	0.253	0.33	10	4	0.00422	131.5

[a] Using Watkins (2003) count of 20,000.

[b] Using Roman and Palumbi (2003) count of 240,000.

[c] Area density based on global estimate.