Is the ocean really getting louder?

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ABSTRACT

In 1975 Donald Ross indicated a long term trend of low frequency anthropogenic noise increased 0.55dB/year between 1958 and 1975 (Ross 1976). This trend in ocean ambient noise levels has been due to 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 ambient 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 ambient noise floor may have been significantly higher in 1800 than in the 1958 baseline year of the "Ross Prediction," suggesting that ambient noise levels may be less of a biological aggravator than the particular characteristics of a noise source.

I. INTRODUCTION

Ocean ambient noise has been increasing exponentially 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 noise has occurred toward the end of industrialized whaling, when whale stocks had been so depleted that the fisheries were shut down by the International Whaling Commission because they 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 extinct (e.g. Pacific Right whale), or the current populations are only a fraction of their pre-commercial whaling populations.

Whaling can be divided into two technological eras; pre-industrial, when whalers pursued whales in sailing ships and killed them with hand-thrown harpoons; and post-industrial, when pursuit vessels were motorized and charge-fired harpoons with explosive points were utilized.

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 whales vocalize to some degree. The amplitude of their vocalizations range from 128 – 192 dB re: 1µPa@1m (reference used hereinafter unless otherwise noted) with the majority of sounds occurring in the range of 165–190 dB. With the exception of clicks, foraging clicks of the sperm whales, and song components of the humpbacks, the frequency band for most of these sounds are < 500 Hz (Richardson *et al.,* 1995).

Given the quantity of animals harvested it is likely whale vocalizations were the dominant noise source in the ocean acoustic environment prior to their extirpation and the more recent globalization of engine-driven ship-borne trade.

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. Over the course of the last half 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 ambient sound levels in the ocean (Richardson *et al.,* 1995), accounting for as much as 75 dB - 90dB 1µPa/Hz by 2004 (MacDonald *et al.,* 2006).

The expansion of shipping was concurrent to the decline of industrial whaling so that any ocean ambient noise measurements taken in the mid 1950's would have been 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 after WWII when the Blue whale populations were not high enough to support commercial harvesting; 20,000 total whale kills annually reported from 1946-1962 (excluding Blue), which declined by 1964 to significantly limit all commercial whaling (Mackintosh, 1965).

While there is little correlation between noise characteristics of baleen whale vocalizations and shipping generated noise, with the exception of the dominant noise spectrum being <500 Hz, there may be some approximate equivalency in sound power densities from the respective sources.

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. METHODS

The determination of the noise contribution of whales into the ocean ambient acoustical environment 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

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 current population of whales, add 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.

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

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, (Sperm, Minke) and species that could not be as easily exploited surreptitiously (eastern Pacific Gray), 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 that due to the high kill rates that the post-industrial whale populations suffered, many of the variables incorporating the finer points of "recruitment" and percent of population that remained in “equilibrium” were essentially made moot. 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-dependant 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?

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). As a consequence only certain representative species could be included into the model.

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 upwellings 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):

$$L_n = L_s + 10\log\theta_e - 10\log\alpha_T H + 10\log\delta$$

Where: L_n = ambient sound pressure

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

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

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).

III. RESULTS

Given the range of uncertainties expressed above, these 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.

$$L_n = dB_s + 10log(\rho\theta_e\delta) - 10log(\alpha_T H)$$

Where: dB_s = source level of the call

ρ = the "call density"

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

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

α_T = the attenuation factor for hemispherical/cylindrical propagation, $13\log(d_1/d_2)$

H = Average depth of the ocean, 4 km

δ = density of whales per km^2

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 3 indicate that the once-abundant species of Mysticetes did make a significant contribution to basin-wide ocean noise levels.

In terms of bio-acoustic precedents, the bio-acoustic 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 the mammal vocalizations are the dominant noise contributors to the soundscape.

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

IV. Discussion

Natural ambient noise due to non-biological factors

The ocean is not always a 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 exceeding the vocalization levels of marine animals. Occasional earthquakes may also exceed the vocalization levels of marine animals; McCauley *et. al.* (2000) cites a level of 272dB re: 1 μPa-m peak.[2]

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 and then drops off at 5 – 8dB per octave. This equates to 100 – 120 dB re 1 μPa depending on sea state (a conversion factor of +62dB will be used for Wenz 1962 hereinafter[3]).

Heavy precipitation can increase the noise in the 1kHz – 10kHz band to 113 dB re 1 μPa. Measurements referred to in Wenz (1962) were taken between 1945 and 1962 which crosses over the decline and nadir of commercial whale populations and the lowest levels of commercial transportation noise (due to restricted merchant shipping during

[2] 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.

[3] $20\log_{10} 20\mu Pa$=26dB (sound power) + $10\log_{10} 3500\rho$ (water density) = 35.5dB (sound intensity) = 61.5dB

World War II) and then the rise in mechanized global maritime trade. The conclusion and resulting chart indicates that shipping traffic noise was a dominant contributor of noise between 100Hz – 1kHz when these measurements were collated.

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 $\mu Pa^2/Hz$ 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:1$\mu Pa/Hz^{1/2}/m$).

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[4]" 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.5] 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 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 the human experience of the environment.

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

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.

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 above, and possibly louder 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.

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.

So while the 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. Understanding 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.

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

Species	Area	Population Estimate	Source
Humpback	Global	115,000	Oceanus (1989)
Humpback	Global	125,000	Fisheries Service (1991)
Humpback	North Atlantic	20,000	Watkins (2003)
Humpback	North Atlantic	240,000	Roman and Palumbi (2003)
Sperm	Global	240,000	Oceanus (1989)
Sperm	Global	1,100,000	Taylor *et al.,* (2008)
Sperm	Global	1,110,000	Whitehead (2002)
Sperm	North Pacific	1,260,000	Rice (1989)
Bowhead	Global	30,000	Oceanus (1989)
Bowhead	Global	50,000	Woodby and Botkin (1993)
Blue	Global	228,000	Oceanus (1989)
Blue	S. Hemisphere	350,000[a]	Clapham and Baker (2002)
Fin	S. Hemisphere	750,000[a]	Clapham and Baker (2002)
Fin	North Atlantic	360,000	Roman and Palumbi (2003)
Fin	Global	548,000	Oceanus (1989)

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

Table II. Characteristic vocalizations of five species of Mysticetes. dB_s = source level of the call; ρ = "call density".

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

Table III. Data calculations.

Species	dB_s	L_s	ρ	θ_e	α_T	H	$\delta(km^2)^{-1}$	L_n
Humpbacks N. Atlantic	159	158.6	0.920	0.33	13	4	0.00049	103.5
Fin N. Atlantic	186	174.8	0.075	0.33	13	4	0.00211	126.1
Blue N. Pacific	184	176.8	0.191	0.33	13	4	0.19000	147.7
Blue NE Pacific	186	180.9	0.311	0.33	13	4	0.19000	151.8
Blue So. Hemisphere	188	182.0	0.253	0.33	13	4	0.00422	136.4