Is the ocean really getting louder?

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In 1975 Donald Ross indicated a long term trend of low frequency anthropogenic noise increase of 0.55dB/year between 1958 and 1975. This trend in ocean ambient noise levels due to expansion in global shipping 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 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.

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.

Introduction

Ocean ambient noise has been increasing exponentially since the industrialization of global shipping (Andrew et al. 2002,[1] McDonald et al. 2006,)[2] and expansion in offshore fossil fuel exploration and production. There is both concern and evidence that this noise is compromising communication channels of marine mammals (Parks et. al. 2010) [3]. 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,[4]).

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, and while some populations seem to have recovered (Minke and Sperm whales), some 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, captured and killed them with hand-thrown harpoons, and post-industrial; with the motorization of pursuit vessels and the use of charge-fired harpoons with explosive points.

Post industrial whaling not only exponentially increased the catch rates, it also allowed the harvesting of larger and faster whales The dominant commercial species were initially Right, Bowhead, Humpback, Gray, and Sperm whales (Townsend 1935) [5]. Post industrial whaling technologies allowed for the pursuit of the larger rorquals (Blue Sei, and Fin).

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 most of these sounds are < 500 Hz (Richardson et. al. 1995[6]).

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. The global shipping fleet began expanding from 1950's to 1998 the shipping fleet expanded from ~30,000 vessels (~85 million gross tons) in 1950 to over 85,000 vessels (~525 million gross tons) in 1998 (NRC 2003)[7]. Incidental noise generated by ships contributes significantly to low-frequency ambient sound levels in the ocean, (Richardson et al. 1995)[8] accounting for as much as 75 dB - 90dB 1µPa/Hz by 2004 (MacDonald et. al. 2006,)[9]

The expansion of shipping was concurrent to the end of commercial 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 population counts (Blue whale 20,000 – 30,000 p/a kills reported from 1930 – 1940, finished post WWII; 20,000 p/a total whale kills reported from 1946-1962 (excluding Blue), declined by 1964) (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.

Methods

Determining the magnitude of the noise contribution of whales to the ocean ambient acoustical environment should be as simple as 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 sprinkling these individual "noise units" across the subject habitat to represent an approximation of whale/habitat density.

Three variables in a carnival of uncertainties:

The three variables in this simple model are:

N = Total Quantity 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 community that remains at equilibrium. The initial rate of decline in total population – that is, the fraction lost in the first year – is $(1 - \delta_i)(1 - e^{-r}{}_i)$. Then we combined all data using nonlinear mixed-effects models[10], 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.

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)[11] and in which the error margins can vastly increase when there is an incentive to prevaricate (Clapham and Ivashchenko 2009)[12].

As a consequence, whale kill claims typically vary from 30% - 5% 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)[13]. While the Soviet example was particularly egregious, the wide variability in pre-whaling population estimates points to a widespread practice of under-reporting kills.

Species	Area	Population Est.	Source
Humpback	Global	115,000	(Oceanus 1989)[14]
Humpback	Global	125,000	(NOAA 1981[15]
Humpback	North Atlantic	20,000	(Watkins 2003)[16]
Humpback	North Atlantic	240,000	(Roman & Palumbi 2003)[17]
Sperm	Global	240,000	(Oceanus 1989)
Sperm	Global	1,100,000	(Taylor et.al. 2008)[18]

Sperm	Global	1,110,000	(Whitehead 2002)[19]
Sperm	North Pacific	1,260,000	(Rice 1989)[20]
Bowhead	Global	30,000	(Oceanus 1989)
Bowhead	Global	50,000	(Woodby and Botkin 1993)[21]
Blue	Global	228,000	(Oceanus 1989)
Blue	S. Hemisphere	350,000*	(Clapham and Baker 2002)
Fin	S. Hemisphere	750,000*	(Clapham and Baker 2002)
Fin	N Atlantic	360,000	(Roman & Palumbi 2003)
Fin	Global	548,000	(Oceanus 1989)
			* Kills in early 20th century

Table 1: Variability in pre-whaling species population estimates (representative)

The premise of this work is that with the exception of species with relatively high recruitment rates, (Sperm, Minke) and species that could not be as easily exploited surreptitiously (eastern Pacific Gray whale), pre-industrial populations of exploited species (Blue, Fin, Bowhead, Right, and Humpback) were arguably ten times higher than their current populations (Roberts, 2007)[22].

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 thrashing that the post-industrial whale populations suffered, that 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)[23]

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 any 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 vary between regional sub-species due to distributions below and above the equator, (seasonal variations in food supplies, breeding, and social opportunities).

3. 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 disperse over wider areas.
4. Vocalization amplitude as a consequence of proximity to conspecifics, and masking by non-specifics. Are whales subject to "the cocktail effect?"
5. Paucity of data on vocalization depth and thus distance/propagation characteristics of various signals.
6. Paucity of data on sexual dimorphic (mate selection and breeding fitness advertisement) vocalizations in most species.

Additionally we could only use vocalization data which included standardized source level (dB re: 1μPa@1m), typical call duration, and call density (calls/hr.) to derive "ρ" ((Duration * Calls hr $^{-1}$)/3600 sec). As a consequence only certain representative species could be included into the model.

Species	Area	dB_s	Duration	Calls(hr) $^{-1}$	ρ	Source
Blue	N. Pacific	184	16	43	0.191	Oleson et.al (2007)[24]
Blue	NE Pacific	186	38	29.5	0.311	McDonald, et.al (1995)[25]
Blue	Chile	188	36.5	25	0.253	Cummings, Thompson (1971)[26]
Bowhead	Arctic	177	66	16	0.293	Cummings, Holliday (1987)[27]
Humpback	Hawaii	159	828	4	0.920	Kurt M. Fristrup et.al.(2003)[28]
Fin	Global	186	1	270	0.075	Watkins et.al. (1987)[29]
Sei	NW Atlantic	156	1.4	37	0.014	Baumgartner et.al. (2008)[30]
Sei	NW Atlantic	156	1.4	500	0.194	Baumgartner et.al. (2008)

Table 2: Characteristic vocalizations of five species of Mysticetes

Where: dB_s = source level of the call, "Duration" in the duration of the calls in seconds, and ρ is the "call density"

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. Townsend's maps 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 (Townsend 1935).

To overcome some of this uncertainty we have chosen to look at ocean basins as a reverberant model (Ross, 1976):[31]

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

Where: L_n = Ambient sound pressure
L_s = Average noise per whale
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 is average depth
δ is the density of whales in a given 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 50km 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., 2009).[32]

Results: A playpen of approximations

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**

Table 3: Data

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

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.
α_T = the attenuation factor for hemispherical/cylindrical propagation: $13\log(d_1/d_2)$
H = Average depth of the ocean (4km)
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 indicates 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-whaling ocean could be correlated to the dawn chorus of any biologically diverse and well populated habitat wherein the riot of birdcalls is the dominant contribution to the soundscape.

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