SC/66b/IA/12

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INTERNATIONAL WHALING COMMISSION

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ABSTRACT

Blue whale (*Balaenoptera musculus*) populations worldwide have regionally-distinct songs, with multiple distinct songs in the North Pacific Ocean, consisting of low-frequency, long duration call units. In the Northeast Pacific (NEP), the song consists of two units, pulsed A call and tonal B call. Blue whale song in the central and western Pacific consists only of a tonal call. Variability in tonal calls of blue whale songs provides a basis for evaluating possible population structure hypotheses. We investigated such variability at six locations; three in the NEP: Gulf of Alaska (GOA), Washington coast (WA), and Southern California Bight (SOCAL); and three in the central and western Pacific (CWP): Hawaii, Wake Atoll, and Tinian in the Mariana Islands Archipelago. Data were recorded by High-frequency Acoustic Recording Packages deployed generally during 2012 and 2013, however off WA and at Wake data were available only in 2012. Detailed measures of call frequency were taken along the contours of tonal calls at all locations. In the eastern Pacific, the average B call in GOA was higher in frequency than the average call in SOCAL. In addition, the GOA calls had a substantial frequency downshift in the second part of the call, which was not present in SOCAL calls. Calls off WA were intermediate between the two other regions' calls in both parameters. Seasonally, , blue whale B call occurrence in the GOA and SOCAL was concurrent, with a peak in September. Off WA, B call detections persisted at low levels through the fall and early winter. The variation in call frequencies and the co-occurrence of peak calling in distinct areas may suggest blue whales in the NEP form two distinct subpopulations. In CWP, calls of two different frequencies were recorded, but they co-occurred in time and space, making population delineation more challenging.

KEYWORDS: ACOUSTICS, BLUE WHALES, NORTH PACIFIC, MONITORING, POPULATION STRUCTURE.

INTRODUCTION

Before their decimation by whaling, blue whales (*Balaenoptera musculus*) used to be widely distributed across the North Pacific Ocean. Whaling data suggest that historically there may have been three distinct populations in this region: the Northeast Pacific (NEP) population found off the west coast of North America, a population off Japan, and a population occupying a vast region from Aleutians in the north to Hawaii in the south, and west across much of central Pacific Ocean (Thomas *et al.*, 2016). While little is known about the latter two populations, the NEP population has been well studied since the cessation of whaling. Its size has not changed over the last several decades (Barlow and Forney 2007; Calambokidis and Barlow 2004; Campbell *et al.* 2015), leading to discussions on whether this indicates a recovered, stable population (Monnahan *et al.* 2015) or a population that is unable to recover due to external threats (Redfern *et al.* 2013). To understand the status of a population, however, it is important to correctly define its range and understand its interactions with neighboring populations.

Blue whale songs have been proposed as a tool for population delineation as they are regionally-distinct worldwide (McDonald *et al.* 2006). These songs consist of low-frequency, long duration, stereotyped calls produced mainly by males, so they may have a mating function (Oleson *et al.* 2007). In the NEP, the song consists of two units, a pulsed sequence termed A call and a long tonal named B call (Oleson *et al.* 2007). The B call is a long-lasting (10+ s) frequency-modulated call with the greatest intensity third harmonic currently around 45 Hz (Širović 2016). A distinct song has been reported in North Pacific outside of the NEP region, consisting of two to three tonal units (McDonald *et al.* 2006). This song type was recorded from the Aleutian Islands in the north, across the central and into the western Pacific.

Intra-population song variability has not been investigated previously for the NEP stock. On the other hand, some variability in the presence of different song units has been reported across the central and western Pacific (CWP) (McDonald *et al.* 2006), pointing to the possibility of finer sub-division of blue whale stocks in this region. However, previous data are sparse both temporally and spatially thus detailed investigations of fine scale spatial and temporal patterns of blue whale song were not possible. In addition, a detailed examination of frequency features of the calls has not been attempted for calls from this region.

In this paper, we investigate the variation in blue whale song tonal units across the North Pacific Ocean. We propose that through the understanding of fine scale spatial variability in these songs, we can gain further insights to stock delineation and may be able to better understand current status of these populations in the aftermath of the 20th century whaling.

METHODS

Data collection

High-frequency Acoustic Recording Packages, HARPs (Wiggins and Hildebrand 2007) were deployed at six locations in the North Pacific Ocean. The HARPs were bottom-moored, consisting of a redundant acoustic release system, data logger and battery cases, and a hydrophone suspended approximately 10 m off the sea floor. The deployments included three locations in the NEP: Southern California (SOCAL), off Washington (WA), and Gulf of Alaska (GOA), and three locations in the CWP: Hawaii, Wake atoll, and Tinian (Fig. 1). Data at most sites were collected during 2012 and 2013, with exceptions for two sites that had data only in 2012 (Table 1). The HARPs sampled at a rate of 200 kHz with 16-bit A/D quantization. At all sites in the NEP data were sampled continuously, but the deployments in the CWP were sampled on a duty cycle (Table 1). Data were subsequently decimated by a factor of 100, creating a dataset with effective bandwidth up to 1 kHz, to facilitate analysis and calculations in the low frequency range.

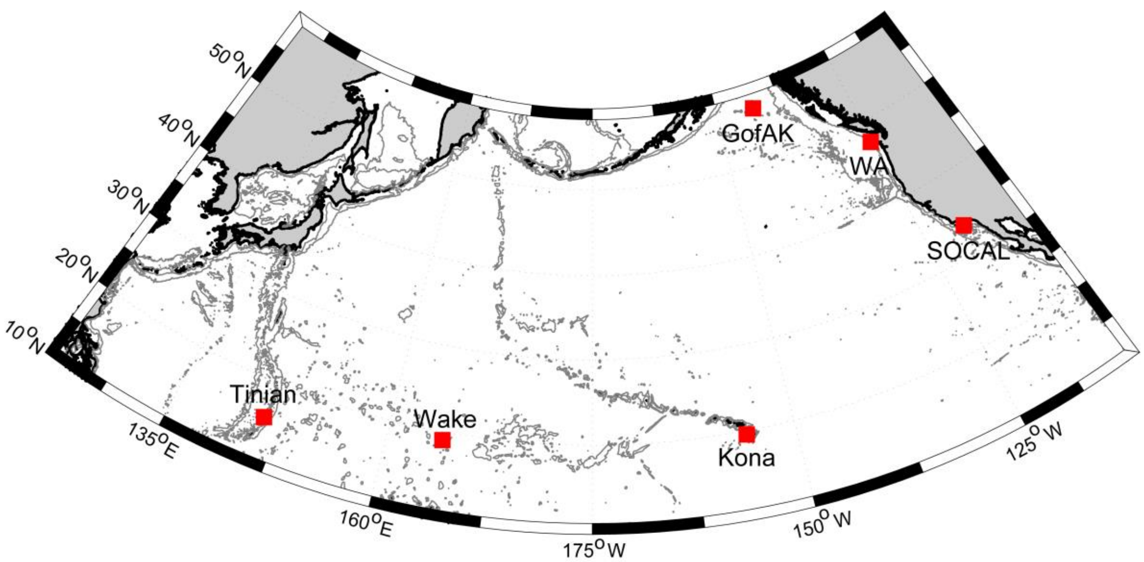

Fig. 1. Bathymetric map of the six HARP deployment locations in the North Pacific Ocean. Light gray lines indicate 1000 and 3000 m depth contours.

Acoustic analysis

Acoustic signal processing was performed using the MATLAB-based (Mathworks, Natick, MA) custom software program *Triton* (Wiggins and Hildebrand 2007), as well as other custom MATLAB routines. Long-term spectral averages (LTSAs) were calculated using the Welch algorithm (Welch 1967). The averages were further calculated from the power spectral densities of non-overlapped 1 s Hann-windowed frames, producing long-term spectrograms with 1 Hz frequency and 5 s time resolutions.

Table 1
Latitude and longitude of data collection sites in the two regions (Northeast Pacific, NEP, and central and western Pacific, CWP), including time periods when data used for detailed call analysis were collected and, when applicable, duty cycle (interval cycle/recording duration in minutes; - indicates data were collected continuously) at which data were recorded.

Region	Site	Latitude	Longitude	Depth (m)	Data start	Data end	Duty cycle
NEP	Gulf of Alaska (GOA)	56°14.61'N	142°45.44'W	990	9 Sep 2012 3 Sep 2013	20 Aug 2013 21 Mar 2014	-
	Washington (WA)	47°30.03'N	125°21.22'W	1390	14 Sep 2012	25 Nov 2012	-
	South. California (SOCAL)	33°30.55'N	119°14.44'W	910	10 Aug 2012 1 Jul 2013	19 Dec 2012 6 Jan 2014	-
CWP	Hawaii	19°34.98'N	156°00.94'W	680	17 Nov 2012 25 May 2013	28 Feb 2013 19 Oct 2013	10/5 15/5
	Wake	19°13.29'N	166°41.56'E	935	25 Feb 2012	3 Jan 2013	30/5
	Tinian	15°02.24'N	145°45.23'E	1000	23 Jun 2012 23 Jul 2013	14 May 2013 15 Jun 2014	6/5 7/5

The recordings were used for fine scale analysis of call frequency characteristics, but also to determine seasonal trends in calling. For call frequency characteristics analysis, LTSAs were manually scrutinized for presence of blue whale tonal calls. In the NE Pacific, only periods with peak calling presence were examined for good quality B calls. For SOCAL and GOA, that means calls were manually detected during July – December for both years of data. Off WA, calls were analyzed from September to November 2012. We attempted to find calls as spread out throughout those months as possible; however, quality of the calls was prioritized. Calls were considered to be good quality if they were high intensity and with low noise background. About 200 calls were detected and logged across the months for each NEP location and year. For CWP sites, a full year of data was scrutinized since less was known about the seasonal occurrence of those calls. At Tinian, data were available for 2012 and 2014 and at Wake they were only available in 2012 (Table 1). All confirmed calls were used for analysis and signal-to-noise ratio was less important, as there were fewer calls and they generally were of lower quality than calls in the NEP.

Using the kernel measurement tool in Triton, multiple frequency measurements were extracted along the contour of the calls at predetermined intervals varying between 0.5 and 2 s. Frequency measurements were extracted from spectrograms calculated with 8000 point-fast Fourier transform (FFT) with 90% overlap and Hann window. Only sections of the contour where the amplitude was higher than a preset background level were used.

All calls sampled on a single day were averaged to avoid over-representing calls from a single animal. The daily averages were then further averaged for each location and year to determine the annual average, representative call for that site and year. The one exception was Hawaii, where data recorded in December 2012 and January 2013 were averaged together and separately from the remainder of the 2012 data. This generally resulted in 11-14 days of data per year per site during peak calling periods in the NEP, and 2-10 days in CWP.

In addition to measurements of call frequency characteristics, to compare temporal trends in blue whale song occurrence in the NEP, all blue whale B calls were automatically detected using spectrogram correlation (Mellinger and Clark 2000) over the two year period of the study (Table 1). Following procedures outlined by Širović (2016), first, an average kernel was calculated from measurements of at least 20 individual B calls, separated by 24 h or more. Then a detector threshold, defined as one that had the precision to recall ratio closest to 1, was determined and the detector was run across all NEP data used in the study. Automatic detections were manually verified for periods of low expected calling, between February and May of each year, and all false detections were removed from analysis. Detection kernels were not developed and automatic detectors were not run for the CWP calls because we lacked sufficient exemplar sounds, and variability among encounters was high.

RESULTS

There were two major differences between blue whale B calls recorded in the NEP: overall frequency of the call and the presence of a notable frequency down-step towards the end of the tonal call (Fig. 2). The frequency of SOCAL calls was about 1 Hz lower than that in GOA. In addition, SOCAL calls did not have a down-step in their frequency contour. The frequency of calls off WA was in between SOCAL and GOA calls, and the step-down was not as large as in GOA, but it was more prominent than in SOCAL. Temporally, blue whale B calls in the GOA and SOCAL both peaked during late summer and early fall (September and October) and they generally stopped being detected in early winter (Fig. 3). More calls were detected in general in the GOA, but because of different bathymetries in these two regions, that site likely monitored a larger area than the SOCAL site, thus an absolute comparison in call abundance is not possible. Off WA, blue whale B calls were detected at lower levels during the summer and fall than at the other two locations, but detections peaked from November to January (Fig. 3).

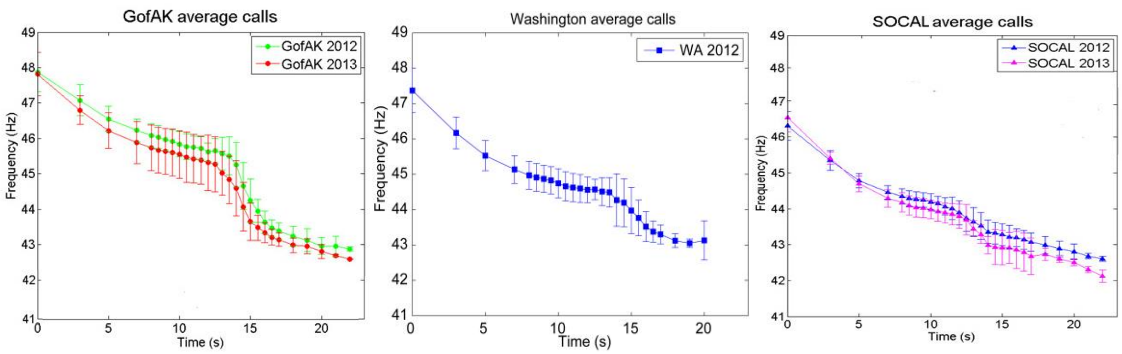

Fig. 2: Average NEP blue whale B calls as measured at three different locations: Gulf of Alaska (left panel), off Washington (middle panel), and in Southern California (right panel) during 2012 and 2013. Error bars represent standard deviation of all average daily calls for each year measurements were made.

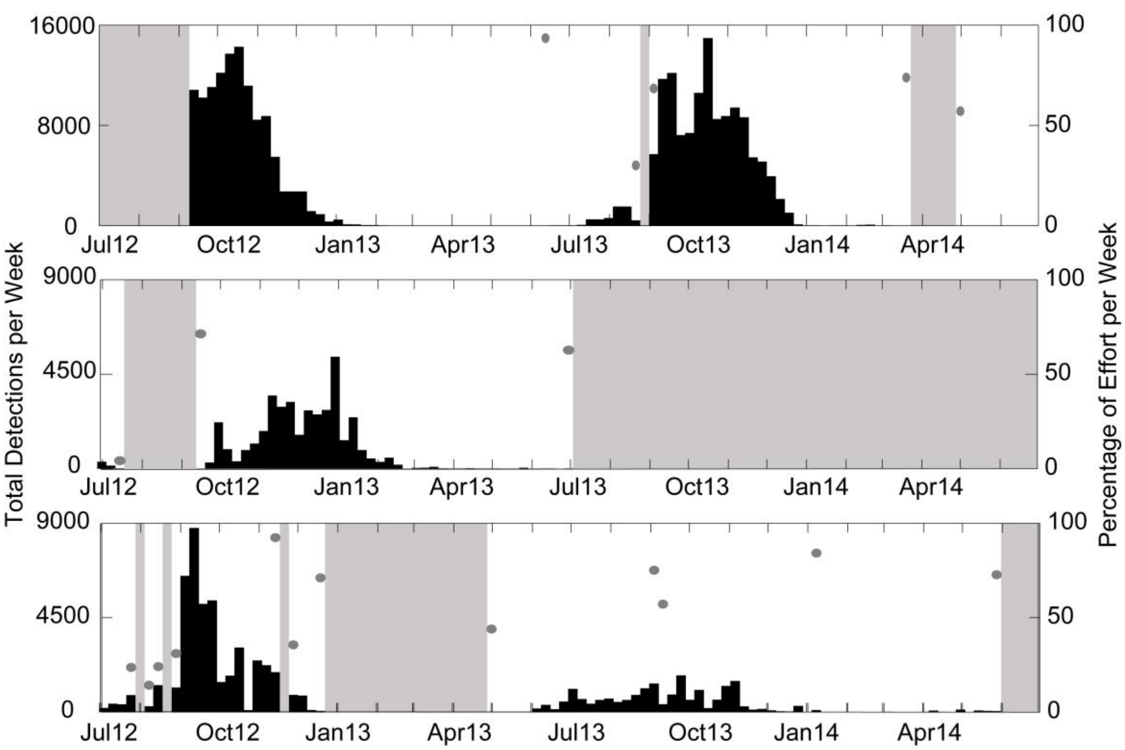

Fig. 3. Weekly detections of NEP blue whale B calls at three different locations: Gulf of Alaska (top panel), off Washington (middle panel), and in Southern California (bottom panel) from July 2012 to June 2014. Grey dots mark what fraction of the week had recording effort when it was not fully recording that week. Dots are only present when there was less than 100% effort. Shaded areas represent periods with no recording effort.

Calls in the CWP could be classified into two different groups based on their frequency: one currently occurring around 20 Hz and the other around 18 Hz (Fig. 4). Both call types exhibited slight, but steady frequency modulation over their duration and 18 Hz calls had shorter overall duration. The 20 Hz call type occurred at all sites where we conducted this analysis, but 18 Hz call was not detected at Wake. There was no clear temporal separation between the occurrence of these two calls; sometimes both call types were detected on the same day. At the Hawaii site, calls were detected June-July 2012, as well as in December 2012 and January 2013. Calls at Wake were detected from May to July 2012, and at Tinian they were detected in July 2012 and May-June 2014.

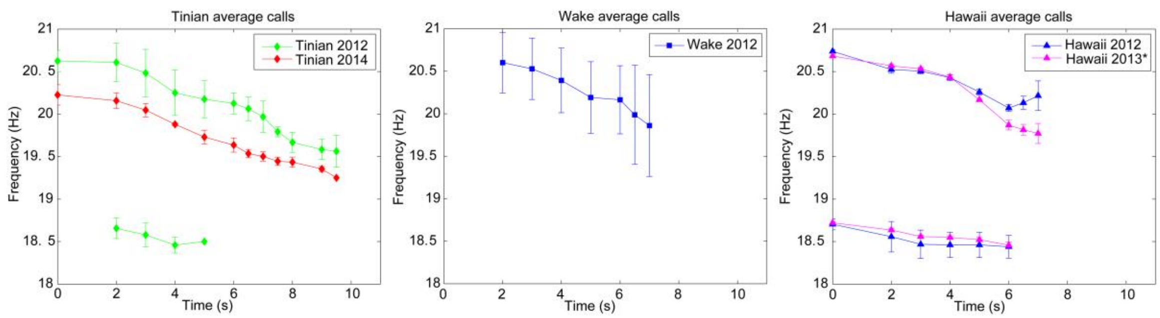

Fig. 4. Average CWP blue whale tonal calls as measured at three different locations: Tinian (left panel), Wake atoll (middle panel), and Hawaii (right panel) during 2012 and 2013 (2014 at Tinian). *Hawaii 2013 marks data from December 2012 and January 2013. Error bars represent standard deviation of all average daily calls for each year measurements were made.

Overall, calls recorded in 2013 were lower in frequency than 2012 calls at nearly all locations with two years of data (Fig.s 2 and 4). In SOCAL and GOA, the average decrease was 0.226 and 0.350 Hz/year, respectively. At Tinian, the average decrease was 0.196 Hz/year. The calls from Hawaii were the only ones where the interannual frequency shift was not evident, but they also did not span full 12 months.

DISCUSSION

It has been a decade since McDonald *et al.* (2006) proposed delineation of blue whale populations based on songs differences, but little work has been done since to further explore fine scale variability of those songs. With these analyses, we are attempting to establish the level of acoustic variability within the populations proposed by McDonald *et al.* (2006). Arguably, the NEP population has been the most studied of all blue whale populations, but this is the first description of fine scale differences in blue whale song across the NEP. The distinction between the GOA and SOCAL calls was rather clear, but the intermediate features of the calls off WA complicate the possibility of clear delineation of these stocks. On closer inspection of individual days' calls, we found that calls measured in September and October had the same frequency characteristics as the SOCAL calls. On the other hand, calls recorded in November, which were the majority of those analyzed, were generally a bit higher frequency (~0.5 Hz) than SOCAL calls, but they were not as high as GOA. We are in process of extending this analysis to more data to evaluate the relationships between calls recorded off WA to those in SOCAL and GOA. We hope our additional analyses will allow us to develop a spatial and temporal model for presence of these two possible stocks of blue whales across this region.

There is some indication that blue whales have relatively recently returned to the Gulf of Alaska (Barlow and Forney 2007; Calambokidis *et al.* 2009), after a long history of exploitation. This expansion could be due to changing population abundances, availability of prey, or different oceanographic conditions (Calambokidis *et al.* 2009). Concurrent with this expansion, separation of the NEP population could be starting via the development of regionally-specific acoustic signatures. Even though there are photo identification matches of whales from California to those in eastern Gulf of Alaska (Calambokidis *et al.* 2009), they are not common and have not been documented in the same year. Given that evidence, a question emerges on the plasticity of blue whale songs. While we know blue whales gradually shift their calling frequency (McDonald *et al.* 2009), we do not know whether the same animal can change its calling beyond this frequency shift. Analysis of fine scale song patterns in known blue whale breeding grounds could offer insights on whether the differences observed in the feeding grounds are maintained on the breeding ground, or if they sing an intermediate, mixed song. By investigating recordings from lower latitude areas, for example data from the seismic recorders deployed in the eastern tropical Pacific in the mid 1990's (Stafford *et al.* 1999), we could see if separation from higher latitudes is maintained in the breeding areas.

It appears that the downward shift in call frequency reported previously (McDonald *et al.* 2009; Širović 2016) has continued. For the NEP population, the frequency shift has been reported between 0.2 and 0.4 Hz/year (McDonald *et al.* 2009; Širović 2016), and our finding is on the lower end of that range. Given that the higher estimates include a longer, more distant time period, it is possible that the rate of decrease is slowing; it may have changed from ~1% per year to ~0.5% in the NEP. In the CWP, the rate we measured was similar to previously reported decrease rate (0.16-0.18) and remains at about 1% (McDonald *et al.* 2009).

Our knowledge of the variability of blue whale song in CWP is sparse, particularly in comparison to the NEP. Visual sightings of blue whales in these waters are exceedingly rare, such that passive acoustic datasets are likely to yield the most data rich opportunity to better understand the status of the species in this vast region. Historically, two populations were found across this region, one broadly distributed in the central Pacific, and the other thought to be confined to the more coastal western Pacific (Thomas *et al.*, 2016). Most of our recording locations are likely within the historic range of the broadly distributed central Pacific population. The occurrence of these songs in the summer is somewhat unexpected, as northern hemisphere animals should be more common in low latitude waters during the winter. The only CWP detections fitting that pattern were December-January detections at Hawaii. It should be noted that many of the CWP summer detections occurred during times when calls similar to Antarctic blue whale calls were also detected in this region. The timing of those calls, even though they occurred further north than may be expected, did match known seasonal presence of these animals in lower latitude waters (Samaran *et al.* 2013; Stafford *et al.* 2004).

An interesting location where both NEP and CWP songs have been recorded is the Gulf of Alaska (Stafford 2003). We are currently conducting a detailed analysis of CWP-type calls in GOA. However, we know that the NEP and CWP songs are temporally separated in the GOA, with CWP song detections occurring in the summer and NEP songs peaking during the fall (Debich *et al.* 2013), providing evidence for niche separation for the two populations. A more detailed analysis of fine-scale CWP-type call features in GOA may provide insights to whether the two call types (20 Hz and 18 Hz) that have spatial and temporal overlap in low latitudes of CWP may be separated in the high latitude feeding grounds. In addition, their occurrence in GOA would resolve the question of whether the somewhat unusual spring and summer timing in CWP is really indicative of southern hemisphere animals, or not.

Concurrent understanding of potential spatial and temporal separation of blue whale songs in high latitude feeding areas and low latitude breeding areas will help us better understand behavioral and physical barriers that these populations encounter. That understanding could lead to potential insights in the mating strategies of this hard to observe species and offer better evaluation of the biological importance of song differences. Thus song variability should be carefully studied and considered when trying to evaluate population structure and status.

ACKNOWLEDGEMENTS
The authors thank techs and engineers at the Scripps Whale Acoustics Lab and Pacific Islands Fisheries Science Center (PIFSC) for instrument development, preparation, deployment, and data processing. Data collection in the NEP was supported by funding from Pacific Fleet Environmental Monitoring program (Chip Johnson). Data collection in the CWP was supported by the PIFSC.

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