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Citation: The Journal of the Acoustical Society of America **108**, 1930 (2000); doi: 10.1121/1.1289668
View online: https://doi.org/10.1121/1.1289668
View Table of Contents: https://asa.scitation.org/toc/jas/108/4
Published by the Acoustical Society of America

Behavioral responses of humpback whales (*Megaptera novaeangliae*) to full-scale ATOC signals

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(Received 22 December 1999; accepted for publication 23 June 2000)

Loud (195 dB *re* 1 μPa at 1 m) 75-Hz signals were broadcast with an ATOC projector to measure ocean temperature. Respiratory and movement behaviors of humpback whales off North Kauai, Hawaii, were examined for potential changes in response to these transmissions and to vessels. Few vessel effects were observed, but there were fewer vessels operating during this study than in previous years. No overt responses to ATOC were observed for received levels of 98–109 dB *re* 1 μPa. An analysis of covariance, using the no-sound behavioral rate as a covariate to control for interpod variation, found that the distance and time between successive surfacings of humpbacks increased slightly with an increase in estimated received ATOC sound level. These responses are very similar to those observed in response to scaled-amplitude playbacks of ATOC signals [Frankel and Clark, Can. J. Zool. **76**, 521–535 (1998)]. These similar results were obtained with different sound projectors, in different years and locations, and at different ranges creating a different sound field. The repeatability of the findings for these two different studies indicates that these effects, while small, are robust. This suggests that at least for the ATOC signal, the received sound level is a good predictor of response. [S0001-4966(00)02610-2]

PACS numbers: 43.80.Ka, 43.80.Nd, 43.30.Sf [WA]

I. INTRODUCTION

Humpback whales show behavioral responses to several different human-made stimuli, including vessel, aircraft, active sonars (3.1–3.6 kHz), and possibly seismic exploration (summarized in Richardson *et al.*, 1995). In most of these cases, it is probable that the acoustic component of the stimulus provokes the response. This underlies the principal concern regarding the potential impact of the Acoustic Thermometry of Ocean Climate (ATOC) project on the marine mammals.

In 1993, the ATOC group proposed to measure the temperature of the ocean with an acoustic method (Munk, 1993). Water temperature is the dominant factor affecting the speed of sound in the ocean, so an accurate measurement of sound speed can be used to infer temperature across long distance paths. The ATOC project has used sound projectors located near the sound channel axis off Hawaii and California to transmit an *m*-sequence signal. The *m*-sequence is a sine wave with phase reversals that encode timing information (Au *et al.*, 1997). It has a 75-Hz center frequency and a broadband source level of 195 dB *re* 1 μPa at 1 m. These signals have been detected at various listening stations around the rim of the North Pacific Ocean. Accurate measurements of the travel times of the ATOC signals have resulted in water temperature measurements along the paths between the source and receivers (ATOC Consortium, 1998; Worcester *et al.*, 1999).

Soon after the announcement of the ATOC project in 1993, a Marine Mammal Research Program (MMRP) was established to study the effects of these proposed transmissions on the behavior and distribution of selected marine mammal species in both Hawaii and California. Study species were chosen based on their presumed ability to hear low-frequency signals, their likelihood of being exposed to the ATOC sound, and the feasibility of gathering enough data to draw conclusions. The humpback whale (*Megaptera novaeangliae*) was chosen as the focal species in Hawaii. Humpbacks are seasonally numerous, produce signals below and above the frequency of ATOC, and offer an extensive history of baseline data with well-developed research techniques.

In Hawaii, Frankel and Clark (submitted) found no changes in humpback distribution in response to ATOC transmissions during the 1998 season. There were indications of a response at the Californian study site, where humpback whales were found further, on average, from the source when the ATOC source was transmitting than during no-sound control portions (Calambokidis *et al.*, 1998).

Behavioral responses may be observed without producing changes in spatial distribution. Short-term behavioral changes caused by vessels have been reported by many authors (Baker and Herman, 1989; Bauer, 1986; Frankel and Clark, 1998). These short-term responses have not produced a major shift of whales away from areas of highest vessel density (Forestell *et al.*, 1991; Mobley *et al.*, 1999), although there is evidence that mother and calf pods in West Maui may have moved offshore in response to persistent vessel traffic (Glockner-Ferrari and Ferrari, 1985; Salden, 1988).

Humpback whale behavioral responses to playback of scaled-ATOC signals were examined in 1996 (Frankel and Clark, 1998). ATOC signals were transmitted with a broadband source level of 172 dB *re* 1 μPa at 1 m. Received levels at whales ranged from below ambient noise level (~105 dB) to as high as 130 dB *re* 1 μPa. Humpback

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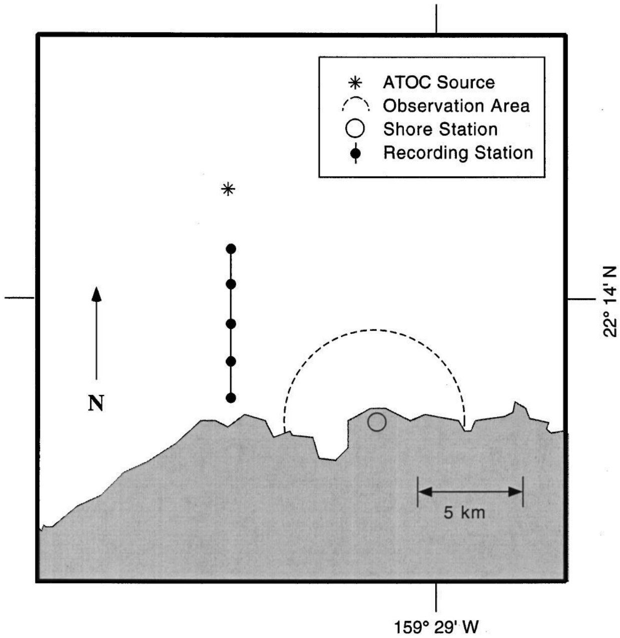

FIG. 1. Schematic for the 1998 study area on the North shore of Kauai, Hawaii is shown. The location of the shore station where observations were made is indicated with the square. The asterisk represents the location of the ATOC source. The observation area is indicated by the arc. The black dots show the position of the five recording stations used to measure the received level of the ATOC source.

whales showed no overt responses to these ATOC playbacks. However, statistical analysis found that both the dive duration and the distance traveled between successive surfacings increased with increasing received level of the ATOC playback signal.

Here we report on the results of behavioral observations conducted using the same methods of the previous study, but with the actual ATOC source replacing the playback speaker.

II. METHODS

A. Overview

The ATOC source was placed 14 km north of Kauai (22.35°N, 159.47°W) at a depth of 850 m, in the summer of 1997. Because low-frequency sound propagation in shallow water is complex and modeling results are unreliable, a transmission loss (TL) study was conducted to measure the received ATOC sound levels within the study area.

Behavioral observations were conducted from 9 February to 24 March 1998 from a shore station (see Fig. 1). Whale observers did not know when ATOC transmissions occurred. Experimental blocks had periodic transmissions while control blocks had none. Times of transmissions during the experimental blocks were varied to create an equal probability of transmission throughout the day. Behavioral observation and visual tracking followed the procedures described in Frankel and Clark (1998).

B. Transmission loss study

Received level (RL) data were collected from 30 October 1997 to 14 December 1997. RL data were collected from a vertical line array (VLA) of calibrated hydrophones using a TEAC RD-101T multichannel digital audio tape recorder. The VLA hydrophones were at depths of 10, 20, 40, and 80 m, encompassing the probable diving range of humpbacks. Ambient noise in the 60–90-Hz band was measured during times without transmissions. The power in the 60–90-Hz band was also measured during ATOC transmissions to determine transmission loss. Data were acquired to computer files using an advanced version of Cornell Canary software (Charif *et al.*, 1995) running on an Apple PowerMac 8100. Sound level measurements were made later using the PowerMeter, a Matlab program that automatically calculated the power in the 60–90-Hz band every second. The 25th percentile value of all of these 1-s measurements made on each transmission recording was returned as the received level measurement. The 25th percentile was chosen to reduce or eliminate the effect of artifacts such as transients and self-noise (e.g., recording vessel hull-slap and noise resulting from array movement through the water) (Frankel and Clark, 1998).

C. Experimental design

During the humpback research season, transmissions were scheduled to be more frequent during the prime observation period (0630 h to 1400 h). In order to insure that the observers remained blind to the experimental condition, the transmission schedule was structured such that there was a multi-day block of control days without transmissions (control) followed by a multi-day block with transmissions (ATOC). During an ATOC block, four ATOC signals were transmitted during daylight hours. Any single transmission consisted of a 5-min ramp-up at a steady rate of 6 dB/min from 165 to 195 dB *re* 1 μPa followed by 20 min at 195 dB. As shown in Fig. 2, transmissions were repeated at 2-h intervals over an 8-h period. The 2 h between transmissions allowed the collection of baseline behavioral data before a transmission.

In order to reduce the chances of an observer guessing whether the source was on or off, the start time of the first transmission occurring on each successive day of a four-day ATOC condition was delayed by 30 min. With this procedure, during any day in the four-day ATOC block, there would be a near-equal probability of a transmission at any time between 0630 and 1400 h Hawaiian Standard Time.

Two nighttime transmissions per day were added at 2000h and 0000h starting on 1 March 1998. This was done when autonomous bottom-mounted acoustic recorders (referred to as ''pop-ups'') were installed, allowing acoustic monitoring at night.

The behavioral analyses examined behavioral rates before, during, and after individual 25-min transmissions within an ATOC block. The null hypothesis tested was that none of the behavioral measures would show a change with respect to ATOC transmissions.

D. Behavioral observation

Behavioral data were collected from a focal pod of whales obtained using visual observation and theodolite

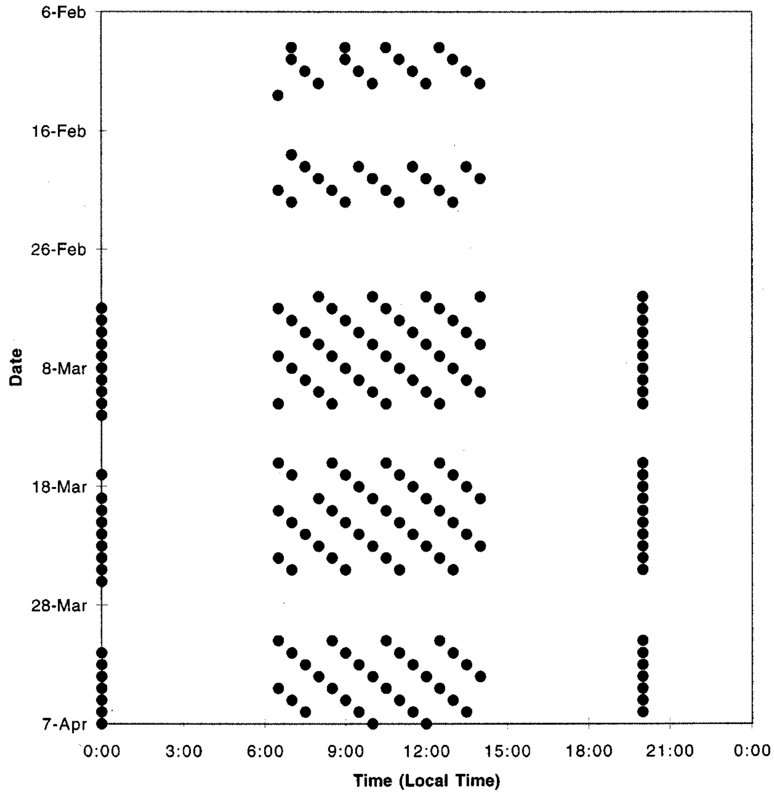

FIG. 2. The ATOC transmission schedule during the 1998 studying showing the pattern of five control and ATOC blocks. The first two transmission blocks included only transmissions during daytime hours. Once the pop-ups were deployed on 1 March 1998, two nighttime transmissions were added to the transmission schedule.

tracking following established MMRP protocols (Frankel and Clark, 1998). Focal pods were chosen on the basis of good sightability, and the likelihood that they would remain in view long enough for adequate data collection. Behavioral data were collected from the focal pod only, while all pods were tracked with the theodolite. Shore station observations documented behaviors of whales that were <5 km from shore, where most (~74%) of the humpbacks are found in the winter (Forsyth *et al.*, 1991). The shore station also documented vessel movement patterns with the same procedures used for whales. The shore station attempted to follow focal humpback pods for as long as possible in order to obtain observations of individual pods before, during, and after an ATOC transmission. Small pods and mother and calf pods were selected preferentially, due to their greater probability of responding to artificial stimuli.

E. Behaviors examined

Based on results from previous studies, the following seven behavioral variables were chosen for analysis. They are the following.

Measure	Unit
Whale speed (or segment speed)	(km/h)
Whale segment duration	(h)
Whale segment length	(km)
Blow rate	(blows/whale/hour)
Surface blow/rate	(blows/whale/surface time)
Surface time	(h)
Dive time	(h)

The first three measures describe movement and are derived from theodolite data. A segment is defined as the line between two successive surfacing locations. The last four measures describe respiratory and dive behavior, and are derived from focal pod observations. The sample sizes for the movement variables were greater than the sample sizes for behavioral measures since the theodolite operator could track multiple pods while the behavioral observer could follow only one pod at a time.

F. Analytical methods

To control for any distinctive behavior patterns of a pod, the analysis focused on potential changes in a pod's behavior between control and ATOC portions (before and during an individual transmission). An analysis of covariance (ANCOVA) test was used so that each pod served as its own control. With this method, the behavioral effects of pod size and calf presence are inherently accounted for in the overall model. The mean value of each behavior was calculated from data prior to and during the ATOC transmission. The control value of each behavior was used as the covariate in an analysis of covariance (ANCOVA) to control for interindividual variability. The effect of pod composition was included in the covariate. ATOC effects were represented as the estimated received ATOC level at the pod. The received level was estimated from the empirically determined transmission loss curve shown in Fig. 3, and the range of the pod from the ATOC source, as determined by theodolite. Descriptors of the nearest vessel present during the observation were included in the analysis in order to test for vessel effects. Frankel *et al.* (1996) found that the closest vessel had a

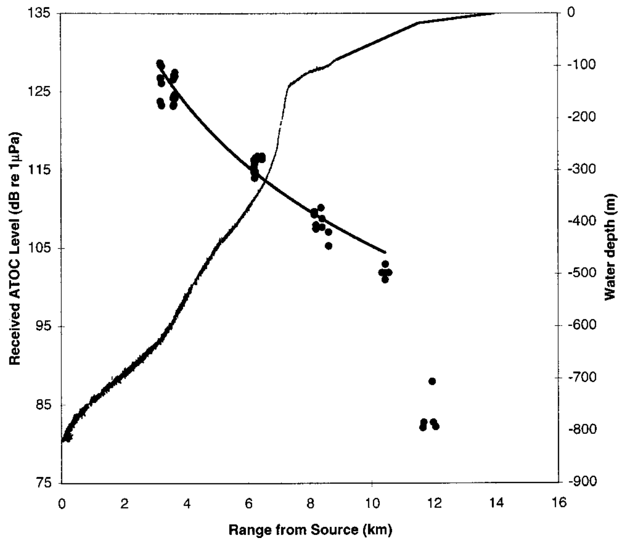

FIG. 3. The measured received sound level is shown as a function of range. Data from a single radial line of measurement stations are shown. These empirical data were used to estimate the received sound level at the whale for the behavioral analyses. The bathymetry underlying these measurements is shown. The sharp upslope rise with increasing range from the source probably contributes to the transition from the deep-water spherical spreading loss [$TL = 19.4^* \log_{10}$ (range)] to the observed $TL = 45.7^* \log_{10}$ (range) function ($R^2 = 0.95$).

greater statistical effect on whale behavior than more distant vessels. The parameters used to describe the vessels were separation between vessel and whale, vessel type (size), vessel speed, number of vessels present, vessel linearity index, and orientation of the vessel relative to the whale (Bowles *et al.*, 1994).

To reduce the number of vessel terms that had to be included in the model and the complexity of these related variables, a principal components analysis (PCA) was conducted on these six vessel descriptors. A standard correlation-based PCA was used. The principal components were included in the model as interaction terms with the vessel presence variable, so that observations made without vessels could also be included in the analysis. The collection of independent variables is referred to as the overall model.

III. RESULTS

A. Transmission loss study

Acoustic recordings were collected between 30 October and 14 December 1997. A total of 265 acoustic samples were taken at various ranges and along six radials. The data for the longest radial, extending south of the source, starting at 3.7 km from the source and ending 12 km south, are shown in Fig. 3. The transmission loss of 66–71 dB over the first 3.7 km indicates that transmission loss initially approximated spherical spreading loss [$TL = 19.4^*\log_{10}(\text{range})$]. The transmission loss then transitioned to an estimated $TL = 45.7^*\log_{10}(\text{range})$. The dramatic increase in transmission loss is most probably a result of the effects of upslope propagation and destructive interference. This transmission loss function was used to estimate the received ATOC level at each pod, based on its distance from the source during transmissions.

It is important to note that the measured ATOC sound level (60–90 Hz) was less than 120 dB *re* 1 μPa at all locations within the 100 fathom contour. The mean ambient noise level in the 60–90-Hz band during the fall, prior to the arrival of humpback whales, was 96 dB *re* 1 μPa ($N = 24\,798$; s.d. = 9.8, sample duration = 1 s). Earlier work conducted off the Island of Hawaii during the winter season estimated ambient noise in the 60–90-Hz band at 105 dB *re* 1 μPa (Frankel and Clark, 1998). This winter value was likely elevated by the contributions from singing humpback whales.

B. Behavioral results

Behavioral data were collected between 9 February and 20 March 1998 when a total of 110 h were spent in 92 focal pod behavioral observation sessions. Observations containing control and ATOC portions were obtained for 65 pods.

Each whale behavior was tested separately with an ANCOVA. The covariate was the value of the behavior in the control portion. The estimated received sound level of the ATOC represented the ATOC effect. The first three vessel principal components were included in the ANCOVA models. The ANCOVA model for each whale behavior is presented and discussed separately.

1. Whale speed

The overall model was statistically significant. The covariate was extremely significant, indicating that the measures of the behavior during the control portion of the observation partially predicts the behavioral measure during the ATOC transmission. This also allows each pod to serve as its own control, as the unique variation of that pod's behavior is controlled for by the covariate. In this model, there was no measured effect of the ATOC transmission or vessels on the speed of whales.

2. Whale segment duration

The overall model was statistically significant, and is shown in Table I. The covariate was statistically significant. The estimated received level of the ATOC transmission had a statistically significant effect on segment duration. The parameter (regression) estimate for the estimated received sound level was 0.010, indicating that as the received sound level increased, the duration of time between successive surfacings increased as well. Figure 4 shows that over the RL range of 98–109 dB the segment duration values, adjusted for the effect of the covariate, increased as a function of the received sound level. There was no effect of vessels on this behavioral measure. The predicted effect of vessel presence was an increase in segment duration.

3. Whale segment length

The overall model was significant, and is shown in Table II. The covariate was again strongly significant. The estimated received level of the ATOC transmission 1 had a

TABLE I. Whale segment duration.

$R^2=0.431$ Source	DF	Sum of squares	Mean square	F value	Pr>F
Model	6	0.536 958 11	0.089 493 02	7.07	0.0001
Error	56	0.708 715 38	0.012 655 63		
Corrected total	62	1.245 673 49			

Factor	DF	Type I SS	Mean square	F value	Pr>F
Baseline behavior or covariate	1	0.431 681 79	0.431 681 79	34.11	0.0001
Estimated received level	1	0.055 750 00	0.055 750 00	4.41	0.0404
Vessel presence (VP)	1	0.017 877 38	0.017 877 38	1.41	0.2396
VP* Vessel PC1	1	0.002 242 03	0.002 242 03	0.18	0.6754
VP* Vessel PC2	1	0.029 261 58	0.029 261 58	2.31	0.1340
VP* Vessel PC3	1	0.000 145 32	0.000 145 32	0.01	0.9150

Parameter	Estimate	T for H0: Parameter=0	Pr>|T|	Standard error of estimate
Intercept	−1.035 362 537	−1.65	0.1054	0.629 123 78
Baseline behavior or covariate	0.747 597 121	4.69	0.0001	0.159 413 13
Estimated received level	0.010 651 831	1.69	0.0967	0.006 304 25
Vessel presence	0.062 539 695	1.74	0.0871	0.035 912 78
VP* Vessel PC1	−0.020 621 711	−1.14	0.2574	0.018 023 17
VP* Vessel PC2	−0.028 426 789	−1.52	0.1342	0.018 706 21
VP* Vessel PC3	−0.001 743 626	−0.11	0.9150	0.016 271 49

Note: The ANCOVA results for whale segment duration are shown. The estimated received level of the ATOC signal predicted that segment duration would increase with received sound level. Vessel presence was a near-significant predictor as well.

significant effect on segment length as well. The parameter (regression) estimate was 0.089. Figure 5 shows that over the RL range of 98–109 dB the adjusted segment length increased as received level of the ATOC signal increased. There was no statistically significant effect of vessels on this behavioral measure. Vessel presence and the first two vessel principal components, however, were close to being significant ($0.05<p\leq 0.10$). Vessel presence would lead to an increase in the segment length. The other two vessel principal components would predict smaller decreases in segment length. These two principal components were primarily combinations of the number of vessels, their linearity index, speed separation from the whale, and type. Increases in all of these tended toward decreasing segment length.

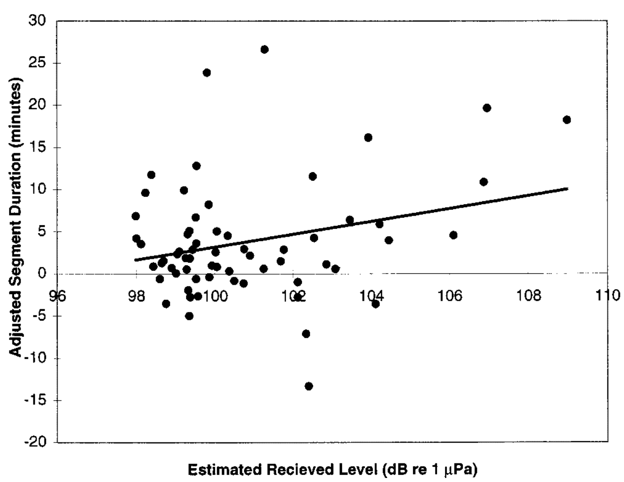

FIG. 4. Segment duration was first adjusted to remove the effect of the covariate (control portion segment duration). The adjusted durations were then plotted against estimated received ATOC sound level. The regression line shows the slight increase in segment duration as received ATOC sound level increases.

4. Blow rate

The overall model was not statistically significant, indicating that there were no measured effects of ATOC or vessels on blow rate.

5. Surface blow rate

The overall model was statistically significant [$F(4,14)=4.36$, $p=0.0268$]. There was no effect of ATOC sound level on blow rate; however, the presence of vessels affected the surface blow rate. The parameter estimate was −0.009, indicating a decrease in surface blow rate when vessels were present. The third principal component was nearly statistically significant ($p=0.067$). Its trend was also toward decreased surface blow rate. The third principal component essentially represents the relative orientation score. Therefore, the trend was for surface blow rate to decrease as whales and vessels were oriented toward each other.

6. Surface time

The overall model was statistically significant. None of the effects, other than the covariate, were significant, indicating that there was no measurable effect of ATOC or vessels on the amount of time whales spent at the surface.

7. Dive time

The overall model was not statistically significant, indicating that there were no measured effects of ATOC or vessels on dive time.

TABLE II. Whale segment length.

$R^2=0.441$ Source	DF	Sum of squares	Mean square	F value	Pr>F
Model	6	9.312 958 68	1.552 159 78	7.77	0.0001
Error	59	11.789 601 89	0.199 823 76		
Corrected total	65	21.102 560 57			

Factor	DF	Type I SS	Mean square	F value	Pr>F
Baseline behavior or covariate	1	4.703 723 00	4.703 723 00	23.54	0.0001
Estimated received level	1	3.342 953 24	3.342 953 24	16.73	0.0001
Vessel presence (VP)	1	0.319 296 02	0.319 296 02	1.60	0.2112
VP* Vessel PC1	1	0.150 407 89	0.150 407 89	0.75	0.3891
VP* Vessel PC2	1	0.410 021 33	0.410 021 33	2.05	0.1573
VP* Vessel PC3	1	0.386 557 20	0.386 557 20	1.93	0.1695

Parameter	Estimate	T for H0: Parameter=0	Pr>|T|	Standard error of estimate
Intercept	−8.613 514 169	−3.57	0.0007	2.414 127 79
Baseline behavior or covariate	0.293 449 973	1.91	0.0611	0.153 692 76
Estimated received level	0.089 222 893	3.69	0.0005	0.024 210 14
Vessel presence	0.282 921 564	1.98	0.0522	0.142 772 38
VP* Vessel PC1	−0.120 521 352	−1.72	0.0898	0.069 875 33
VP* Vessel PC2	−0.123 315 510	−1.67	0.1008	0.073 971 59
VP* Vessel PC3	−0.089 942 938	−1.39	0.1695	0.064 667 15

Note: The ANCOVA results for whale segment length are shown. The estimated received level of the ATOC signal predicted that segment duration would increase with received sound level. Vessel presence was a near-significant predictor as well.

C. Abundance of vessels

The number of vessels and the distances between whales and the nearest vessel were compared between 1994 and 1998. The mean number of vessels observed per session in 1994 was 1.66 (s.d.=1.62) and 1.11 (s.d.=1.19) in 1998. Furthermore, the mean separation distance increased from 3.09 km in 1994 to 8.04 km in 1998. The number of boats permitted to launch from the Hanalei River, the only winter-time harbor on the North Shore of Kauai, was reduced between 1994 and 1998 by changes in local regulations. On average, there were fewer vessels in 1998 and they were further away from the whales than in 1994.

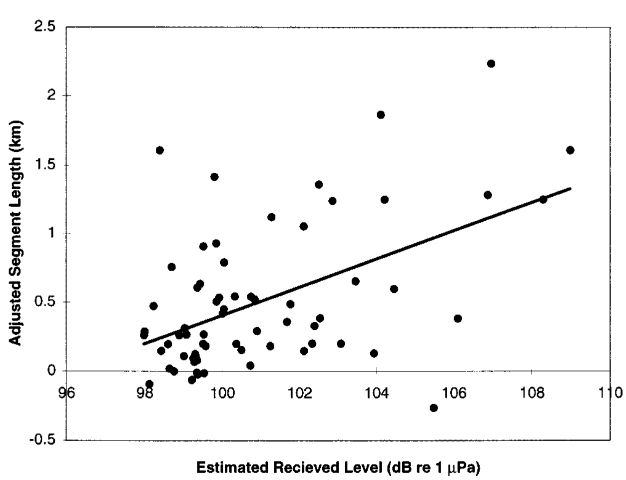

FIG. 5. Segment length was first adjusted to remove the effect of the covariate (control portion segment length). The adjusted lengths were then plotted against received ATOC sound level. The regression line shows the slight increase in segment length as estimated received ATOC sound level increases.

IV. DISCUSSION

The behaviors of humpback whales presented with full-scale (i.e., ''normal'') ATOC sounds were observed using the same methods as in a previous study that documented responses to scaled playbacks of ATOC sounds. In both the previous and current study, the ATOC signals were represented in the analysis as the estimated received sound level rather than a simple ''on/off'' variable.

The analysis of covariance revealed that both the time and the distance between successive surfacings increased with increasing estimated received sound level. This result is consistent with the results of the scaled-ATOC work conducted off the Island of Hawaii in 1996 (Frankel and Clark, 1998). Humpbacks exhibited similar responses to the same ATOC signal at similar received levels. These results indicate that ATOC transmissions produce subtle but repeatable, predictable short-term behavioral changes in humpback whales.

The striking similarity between the 1996 and 1998 responses addresses a long-standing issue regarding whale reactions to noise. Earlier work with gray whales found that 50% of the migrating population deflected from their course when the received level of industrial noise reached 116–124 dB *re* 1 μPa. Given the limitations in source level in the gray whale study (~162 dB *re* 1 μPa), the 50% avoidance occurred at ranges of ~100 m from the playback vessel. It was recently suggested that the whales responded more to the proximity of the source than to the received level (Ellison and Weixel, 1994). The scaled ATOC playback experiment (Frankel and Clark, 1998) and the current study used two different sound sources with vastly different source levels (172 dB vs 195 dB *re* 1 μPa at 1 m). Both studies documented similar responses at similar received levels (98 to 130 dB), but at vastly different distances from the source (~100–2000 m vs 8–12 km). This indicates that for the ATOC signal, received level proved to be a better predictor of response than proximity. It is also important to note that the predictions of increased duration and length of movement segments are valid only to received levels of up to 130 dB *re* 1 μPa. Extrapolating to higher received levels is not reliable given the present results and could lead to significant prediction errors.

The conclusion that received level is a good predictor of response does not generalize to all species and signals. Playback of U.S. Navy low-frequency active sonar signals to gray whales evoked strong responses when the acoustic source was in their migratory path. When the source was moved offshore 2 km, there was no response to the signals, even though the received sound levels were comparable (Clark *et al.*, 1999). In this case, received level alone cannot explain the observed behavior.

The only behavior affected by vessels was surface blow rate, although other whale behaviors had near-significant vessel effects. When vessels were present the surface blow rate decreased slightly. During the ATOC playback experiment, surface blow rate was found to decrease as vessel size increased (Frankel and Clark, 1998). In that study, and in most other studies, a greater number of vessel effects were detected. The apparent reduction in vessel effect in 1998 may be explained by the drop in vessel traffic off Kauai from 1994 to 1998.

How comparable are the effects of vessel traffic and ATOC transmissions? The mean estimated received level of the ATOC transmissions at the location of all the focal pods in the analysis ranged from 98.0 to 109.0 dB (mean=101.4 dB; s.d.=2.58; $N=65$). This is less than or equal to typical vessel acoustic stimuli. Frankel and Clark (1998) found that, at higher traffic levels than those seen in the present study, the single vessel closest to the whale affected more behaviors than the ATOC playback stimulus. This suggests that the effects of ATOC signals are roughly comparable to that of low to moderate vessel activity. Both study sites experience much less vessel traffic than humpback habitats off Maui or O'ahu.

The presence of vessels and the occurrence of ATOC transmissions were found to produce short-term behavioral changes. The question needing to be addressed is that of biological significance and cumulative impact. Do these subtle short-term responses have any long-term implications? Humpback whales frequently encounter vessels throughout most of their range in Hawaii and major portions of their range in Alaska. Increased vessel traffic may be responsible for a shift in the distribution of mother and calf pods off Maui (Glockner-Ferrari and Ferrari, 1985; Salden, 1988). However, this effect was not seen when all pod types were considered (Forestell *et al.*, 1991).

During the 25 years that humpbacks have been studied in Hawaii, vessel traffic has steadily increased. There is now evidence that the population of humpbacks is increasing. A comparison of statewide aerial surveys conducted in 1976–1980, and repeated in 1990, found that sighting rates had increased throughout the state (Mobley *et al.*, 1999). The most recent population estimates based on photographic resightings reported a much higher population level than earlier estimates (Calambokidis *et al.*, 1997; Cerchio, 1998). Therefore, it seems that if vessel interactions do have some negative long-term effect, it is not sufficient to prevent the population from growing. ATOC transmissions will likely have even less long-term impact on the population than vessels because ATOC affects a much smaller fraction of the humpback habitat (approximately 157 km^2) than vessels. Furthermore, ATOC can affect behavior only on the wintering grounds whereas vessels may be present on the wintering and summering grounds as well as during migration.

The results of the research presented here and conducted earlier with humpback whales indicate that the hearing range of humpback whales encompasses the 75-Hz ATOC signal. However, whales within 12 km of the source show only subtle, short-term effects on their surface behaviors. They do not show any immediately obvious response to the ATOC signal at received levels <130 dB. They do not abandon their coastal habitat adjacent to the offshore ATOC source. They returned to that habitat in the year following a season of exposure to that source. We conclude that the present operation of the ATOC source off Kauai is not sufficient to cause biologically significant changes in behavior for the humpback population wintering off Hawaii. However, we emphasize that this conclusion cannot be generalized to the effects of cumulative impacts from multiple sources including ATOC, and a suite of other man-made sources such as local vessel traffic, commercial vessel traffic, oil and gas seismic surveys, and various sonars. Understanding cumulative impacts will require much broader knowledge of habitat use, behavioral ecology, underwater acoustics, and man-made noise in the ocean.

ACKNOWLEDGMENTS

We would like to thank a number of people for helping to make this research and this report possible. We would first like to thank the members of the 1994 and 1998 research teams, who collected the data used in this report. They are Vicki Beaver, Greg Campbell, Alison Craig, Janet Doherty, Megan Ferguson, Bridget Ferris, Christine Gabriele, Mia Griafalconi, Leila Hatch, Eric Howarth, Matt Irinaga, Gene Kent, Tom Kieckhefer, Tom Norris, Susan Reeve, Mari Smultea, Dave Weller, and Ann Zoidis. At the Cornell Laboratory of Ornithology, the support of Tom Calupca, Russ Charif, Brian Corzilius, Kathy Dunsmore, Melissa Fowler, Kurt Fristrup, Connie Gordon, Marguerite McCartney, and Harold Mills was invaluable. Peter Worcester and Susie Pike at the Scripps Institution of Oceanography were very helpful as were Bruce Howe, Jim Mercer, and Shirley Westlander of the Applied Physics Laboratory of the University of Washington. Special thanks to Robert C. Gisiner of the Office of Naval Research for helping to support this research. The

MMRP Advisory Board under the Chairmanship of W. John Richardson has provided many helpful comments and review throughout the years. Research was conducted under permits issued by the National Marine Fisheries Service (No. 970) and the State of Hawaii Permit (PRO98-06). The comments of two anonymous reviewers were appreciated and contributed to this manuscript. Funding was provided through the Advanced Research Projects Agency and this work relates to the Advanced Research Projects Agency Grant No. MDA972-93-1-0003 funded by the Strategic Environmental Research and Development Program (SERDP). The United States Government has a royalty-free license throughout the world in all copyrightable material herein. Additional funding was supplied through SERDP Grant No. 00014-97-1-0571.

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