Effect of underwater seismic surveys on molting male Long-tailed Ducks in the Beaufort Sea, Alaska

Deborah L. Lacroix, Richard B. Lanctot, John A. Reed, and Trent L. McDonald

Abstract: Large numbers of Long-tailed Ducks (*Clangula hyemalis*) (10 000 – 30 000) undergo a postnuptial wing molt along barrier islands of the Beaufort Sea, Alaska. To investigate the potential effects of underwater seismic activities on this species, we monitored the number and diving behavior of molting Long-tailed Ducks before, during, and after seismic activities in a seismic area and two control areas nearby between July and September 2001. Aerial surveys documented a decline in duck numbers in both seismic and control areas during the period of seismic activity. We used automated data-collection computers to monitor the presence and diving behavior of radio-equipped Long-tailed Ducks residing within 2.5 km of a series of computer setups located along the barrier islands and on the mainland. A statistical analysis based on a modified before–after control–impact approach found no difference in indices of site fidelity or diving intensity between the seismic area and two control areas. Thus, we found no effect of seismic activity on movements and diving behavior of molting Long-tailed Ducks. These results should be evaluated carefully, however, as logistical and ecological factors limited our ability to detect more subtle disturbance effects. We recommend additional studies on other bird species to fully understand the effects of underwater seismic testing.

Résumé : Un grand nombre (10 000 – 30 000) de hareldes boréales (*Clangula hyemalis*) subissent une mue postnuptiale des ailes dans les îles barrières de la mer de Beaufort en Alaska. Pour déterminer les effets potentiels des activités sismiques sous-marines sur l'espèce, nous avons enregistré de juillet à septembre 2001 le nombre de plongées et le comportement de plongée chez les hareldes boréales avant, pendant et après des activités sismiques dans une zone sismique et dans deux zones témoins adjacentes. Des inventaires aériens ont indiqué un déclin des densités de canards tant dans les zones sismiques que dans les zones témoins durant la période d'activité sismique. Une série de stations d'ordinateurs installés sur les îles barrières et la terre ferme a permis d'enregistrer automatiquement la présence et le comportement de plongée de hareldes boréales munies d'un émetteur radio dans un rayon de 2,5 km. Une analyse statistique de type BACI (avant–après, témoin–impact) modifiée n'indique aucune différence de fidélité au site, ni d'intensité de plongée entre la zone sismique et les deux zones témoins. Nous n'avons donc trouvé aucun effet de l'activité sismique sur les déplacements et le comportement de plongée de hareldes boréales en mue. Ces résultats doivent cependant être interprétés avec prudence, car des facteurs écologiques et logistiques limitaient notre aptitude à détecter des effets plus subtils de la perturbation. Nous recommandons la poursuite des études sur d'autres espèces d'oiseaux afin de pouvoir évaluer adéquatement les effets des effets essais sismiques sous-marins.

[Traduit par la Rédaction]

Introduction

North America's largest oil and natural gas discovery resides in the Alaskan Arctic Coastal Plain along the Alaskan Beaufort Sea (Gilders and Cronin 2000). During the last 25 years, oil and gas development on the North Slope of Alaska was centered largely on state-leased lands onshore in the Prudhoe Bay area. The recent expansion of oil and gas development and exploration into the nearshore waters of the Beaufort Sea has raised concerns for wildlife using these waters and the nearby barrier islands (United States Army Corps of Engineers 1999). Mineral exploration and development that occurs during the open-water season has the potential to impact a large number of waterbirds that use the lagoons and barrier islands in the immediate area. Of the over 35 waterbird species found in these habitats, the Long-tailed Duck (*Clangula hyemalis*) is the most abundant, accounting for nearly 80% of all birds present (Noel et al. 2001; Fischer et al. 2002). Between 10 000 and 30 000 Long-tailed Ducks from Alaska and Canada migrate from

Received 5 May 2003. Accepted 7 October 2003. Published on the NRC Research Press Web site at http://cjz.nrc.ca on 23 December 2003.

D.L. Lacroix,[1] R.B. Lanctot,[2,3] and J.A. Reed. U.S. Geological Survey, Alaska Science Center, Biological Sciences Office, 1011 East Tudor Road, MS 701, Anchorage, AK 99503, U.S.A.
T.L. McDonald. Western Ecosystem Technology, Inc., 2003 Central Ave., Cheyenne, WY 82001, U.S.A.

[1]Present address: Centre for Wildlife Ecology, Simon Fraser University, 8888 University Way, Burnaby, BC V5A 1S6, Canada.
[2]Corresponding author (e-mail: Richard_lanctot@fws.gov).
[3]Present address: U.S. Fish and Wildlife Service, Migratory Bird Management, 1011 East Tudor Road, MS 201, Anchorage, AK 99503, U.S.A.

 doi: 10.1139/Z03-185

their breeding grounds to these lagoons in mid- to late July where they undergo a postnuptial wing molt (Johnson and Richardson 1982; Bartels et al. 1984; Wilbor 1999).

During wing molt, birds are incapable of flight for a period of 3–4 weeks, making them potentially vulnerable to human disturbance (Johnson and Richardson 1982). The wing molt is energetically costly and can be a nutritionally stressful period for sea ducks (Murphy and King 1982; Hohman et al. 1992; Howell 2002). Birds can compensate for these higher energetic needs by increasing foraging time, reducing other nutritionally costly processes, or catabolizing stored nutrients (Ankney 1979). Howell (2002) found that Long-tailed Ducks in the Beaufort Sea meet the energy requirements of feather regrowth through dietary intake rather than use of stored reserves. The lagoons within the central Beaufort Sea support a rich and abundant food source in the form of mysids and amphipods (Griffiths and Dillinger 1981; Craig et al. 1984; Johnson 1984; Wilbor 1999). The area also provides shelter to ducks from wind, wave action, and pack ice (Johnson and Richardson 1982; Brackney et al. 1985). Disturbances, such as those caused by mineral exploration and development, may compromise the ability of Long-tailed Ducks to access and fully use their molting habitats and thus successfully complete their molt. This may be especially true for small sea ducks, such as the Long-tailed Duck, which have relatively higher metabolic rates and store less energy than larger waterfowl species (Goudie and Ankney 1986). Murphy and King (1982) found that deficiencies in the diet might result in the prolonged duration of molt or the malformation of growing feathers.

A human disturbance that may be detrimental to sea ducks is nearshore underwater seismic surveys that are commonly used to explore and map mineral resources located below the surface (Richardson et al. 1995). An open-water marine seismic survey employs intense sound pulses emitted at regular intervals by an array of underwater air guns (Greene and Richardson 1988). The sound returning from the seabed is processed to locate geological formations that may contain producible quantities of hydrocarbons. In addition to the sound that travels downwards into the seabed, the sound from the air guns also travels sideways through the water. The peak noise levels of the seismic pulses exceed those of other industrial activities such as aircraft, ships, dredging, and other construction (Richardson et al. 1995). These noise pulses have been found to cause general avoidance reaction, changes in behavior (e.g., dive cycles, respiration), and displacement of marine mammals such as the common dolphin (*Delphinus delphis*), gray whale (*Eschrichtius robustus*), sperm whale (*Physeter macrocephalus*), and bowhead whale (*Balaena mysticetus*) (Richardson et al. 1995; Goold 1996). Richardson (2001) indicated that some bowheads may remain as far as 24 km from ongoing seismic surveys. This seismic activity could displace and disrupt the behavior of molting Long-tailed Ducks, particularly while diving to feed (Goudie and Ankney 1986).

In August 2001, BP Exploration (Alaska) Inc. contracted Western Geophysical to conduct a three-dimensional geophysical survey in the Simpson Lagoon of the Beaufort Sea (Richardson 2001). We evaluated the effects of this underwater seismic activity on molting Long-tailed Ducks residing in this area. We predicted that Long-tailed Ducks would be displaced from the area where seismic activity was occurring. We also predicted that Long-tailed Ducks would dive at different rates when seismic activities were occurring, although we could not predict whether they would dive more or less. We believe that this represents the first study to evaluate the potential effects of underwater seismic surveys on sea ducks.

Methods and materials

Study area

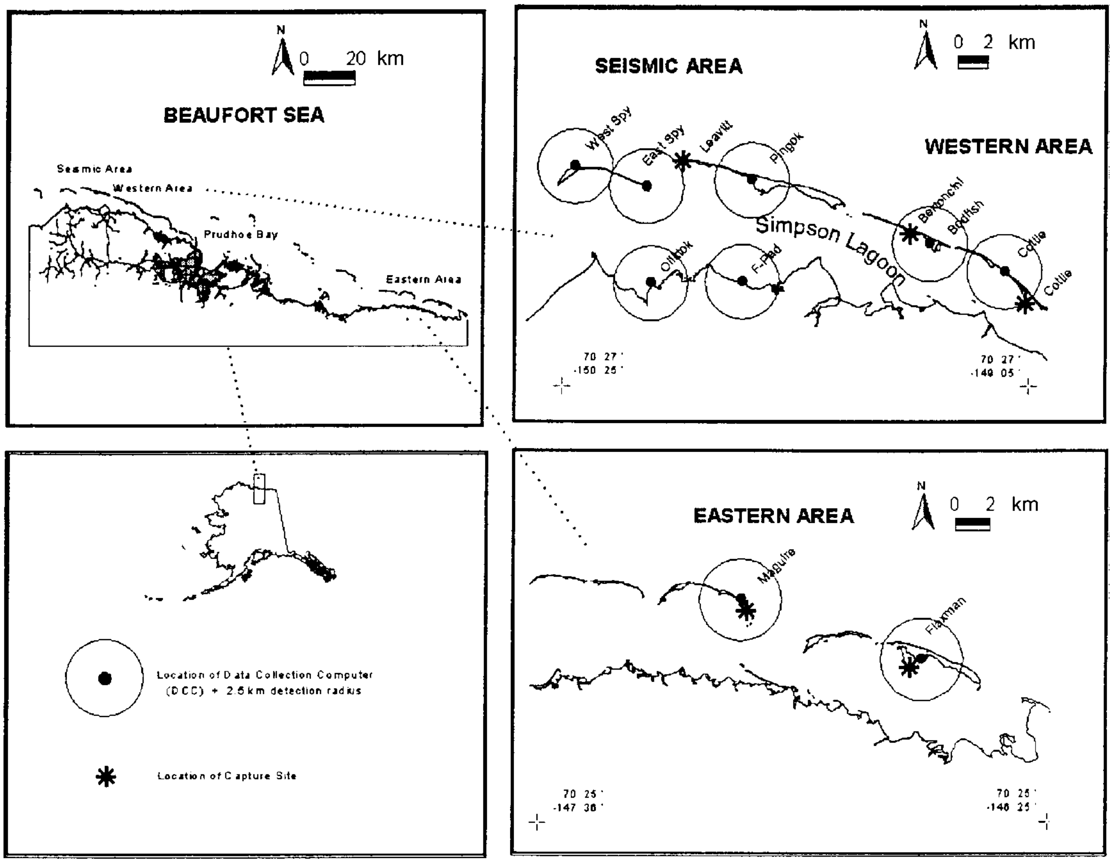
This study was conducted along a line of barrier islands in the central Beaufort Sea, Alaska (70°15–30′N, 150°30–45′W) (Fig. 1). The area extends from the Colville to the Canning rivers and lies just off the coast of the Prudhoe Bay oil field in Alaska. The study area was divided into three treatment areas: (1) a seismic area located near Spy and Pingok islands, (2) an adjacent western control area near Bodfish and Cottle islands, and (3) an eastern control area approximately 50 km east located along the Maguire and Flaxman islands (Fig. 1). We also established three time periods defined as preseismic activity, seismic activity, and postseismic activity.

Seismic-survey protocol

From 4 to 26 August 2001, Western Geophysical conducted a three-dimensional reflection survey for hydrocarbon deposits in the nearshore waters of the western portion of the Simpson Lagoon approximately 48 km from Prudhoe Bay (Richardson 2001). Five vessels, ranging in length from 23 to 41 m, were used on the seismic survey. Two source vessels were used for setting off air-gun explosions, two vessels were used to deploy cable, and one vessel was used for multiple purposes. Seismic activities were conducted systematically in discrete sections until the entire area was sampled. Activities included surveying each section to obtain water depth, laying receiving cables along uniformly spaced transect lines on the ocean floor, towing and discharging air-gun arrays perpendicular to the cables, and retrieving cables from the ocean floor. Air guns were towed by one of two source vessels depending on the bathymetry of the area. In shallow water (i.e., within the lagoon), a smaller vessel was used, which deployed two identical clusters of four (1.3 L) sleeve-type air guns over the port and starboard sides of the vessel. The air guns released high-pressure underwater air blasts every 8–10 s. On the ocean side of the islands where the water was deeper, a larger vessel was used to tow 12 sleeve-type air guns of various individual volumes (1.3–2.5 L for a total of 19.8 L), which discharged every 12–24 s. Clusters of geophones and hydrophones, which were attached to the receiving cables at 50-m intervals, registered the subsurface signals and sound vibrations and transmitted the information along the cable to the recording/telemetry vessel.

The location of all vessels and the time of day when seismic activity occurred were recorded on digital hydrographic charts. These charts were used to delineate a region that was directly disturbed each day, allowing us to classify each data-collection site relative to a particular disturbance on a given day.

Fig. 1. Location of the seismic, western control, and eastern control areas along the Beaufort Sea in northern Alaska. The location and 2.5 km radius detection area of nine data-collection computer systems and capture locations are also presented along with the oil infrastructure (i.e., roads, drill sites, and pipelines) of the Prudhoe Bay oil field.



Aerial surveys

To examine changes in the abundance and distribution of ducks, aerial counts of Long-tailed Ducks were conducted during the preseismic, seismic, and postseismic periods along the inside and outside edges of barrier islands located in the western portion of the study area (Thetis to Stump islands). No surveys were conducted in the eastern control area. One preseismic survey occurred on 24 July 2001, two seismic surveys were conducted on 6 and 15 August 2001, and one postseismic survey took place on 7 September 2001. Persistent fog kept us from surveying Thetis Island and the ocean side of most islands on 15 August, and Thetis Island was not surveyed on 7 September 2001. To standardize comparisons between surveys, we excluded counts from Thetis Island and eliminated the incomplete survey conducted on 15 August 2001 when comparing counts from the ocean and lagoon side of the islands. Surveys were conducted in mid-afternoon to evening (start times ranged from 1245 to 2050) and occurred only on calm days. Restricting surveys in this way maximized our ability to count ducks and likely reduced the amount of measurement error in survey counts (Johnson and Gazey 1992; Fischer et al. 2002).

Long-tailed Ducks were counted from a Cessna 185 aircraft traveling 90 m above the ground at 140 km/h. A single observer counted all ducks within a 400-m strip between the plane and the barrier islands. The data was transcribed into a tape recorder and the locations of all ducks were marked on 1 : 50 000 maps of the Simpson Lagoon area by a separate observer. Additionally, the second observer photographed flocks when feasible so that estimates of flock size could be compared with counts of ducks taken from enlarged images. The observer counts were between –14% and +86% different from the counts derived from photographs (34.7 ± 17.7% (mean ± SE), $N = 6$). Consequently, we increased observer counts by the mean percent difference between observer and photograph counts.

Capture and detection of radio-equipped Long-tailed Ducks

We captured Long-tailed Ducks by driving flocks of flightless adults into corral traps set along roosting beaches on the barrier islands during late July and early August 2001. A subsample of males was equipped with 12-g radio transmitters that were glued and anchored to their backs with subcutaneous arrow attachments (Pietz et al. 1995). Radio transmitters emitted a signal 60 times/min and had mortality sensors that activated when no movement occurred for 8 h.

Data-collection computers (DCCs) connected to fixed antennas were placed near each of the Long-tailed Duck capture sites to maximize detection of the radio-marked birds. Five DCC towers were erected within the seismic area (three on barrier islands and two on the mainland) and two DCC towers were erected in each of the control areas (all on barrier islands) (Fig. 1). Deep-cycle 12-V batteries attached to solar panels powered the radio receivers and DCCs.

The DCCs recorded the presence and number of pulses of each radio transmitter within 2.5 km for a 45-s period before switching to the next transmitter frequency. Thus, radio transmitters were monitored between one and three times per hour depending on the number of radio-equipped birds located near a site. We could not detect more subtle movements of ducks that might have occurred within the 2.5-km detection area. We also monitored a nearby reference radio transmitter at each DCC tower that enabled us to determine if and when the tower was functioning.

Discharged batteries and downloading of data resulted in days with no data or less than 24 h of data. To determine how the hours of operation per day affected the number of radio-equipped ducks detected by DCCs, we plotted the cumulative proportion of radios detected by hour for each DCC in each day. This analysis was limited to days when DCCs operated 24 h and included only radio-equipped ducks originally captured near a given DCC. We then averaged these proportions across days and DCCs. We found that most radios (84.6 ± 2.5% (mean ± SE)) were detected after 6 h of DCC operation. Consequently, we eliminated 14 DCC days when less than 6 h of data were available. The remaining 19 days kept in the analysis (i.e., days with between 6 and 24 h of data) represented 14 ± 1.4% (mean ± SE) of the days used at the nine DCC sites for data analysis. The remaining DCC data allowed us to determine the proportion of radios in a given DCC area that were present each day. The physical arrangement of the capture sites allowed us to compare the movement of ducks between the seismic area and the western control area and between the western portion (Maguire Island) and eastern portion (Flaxman Island) of the eastern control area (Fig. 1).

We also investigated the behavior of ducks by classifying them as diving or not diving depending on the number of transmitter pulses recorded during each 45-s scan. Radio signals are attenuated by salt water when Long-tailed Ducks dive. Thus, pulse rates below that expected within a 45-s scan interval can be interpreted as coming from diving birds. We considered radio frequencies with 40 pulses or less to represent ducks diving, frequencies with 41–50 pulses to be ducks present but not diving, and frequencies with more than 50 pulses to be erroneous readings (i.e., caused by transmitter interference from other radio sources or when battery power was low).

Statistical analysis

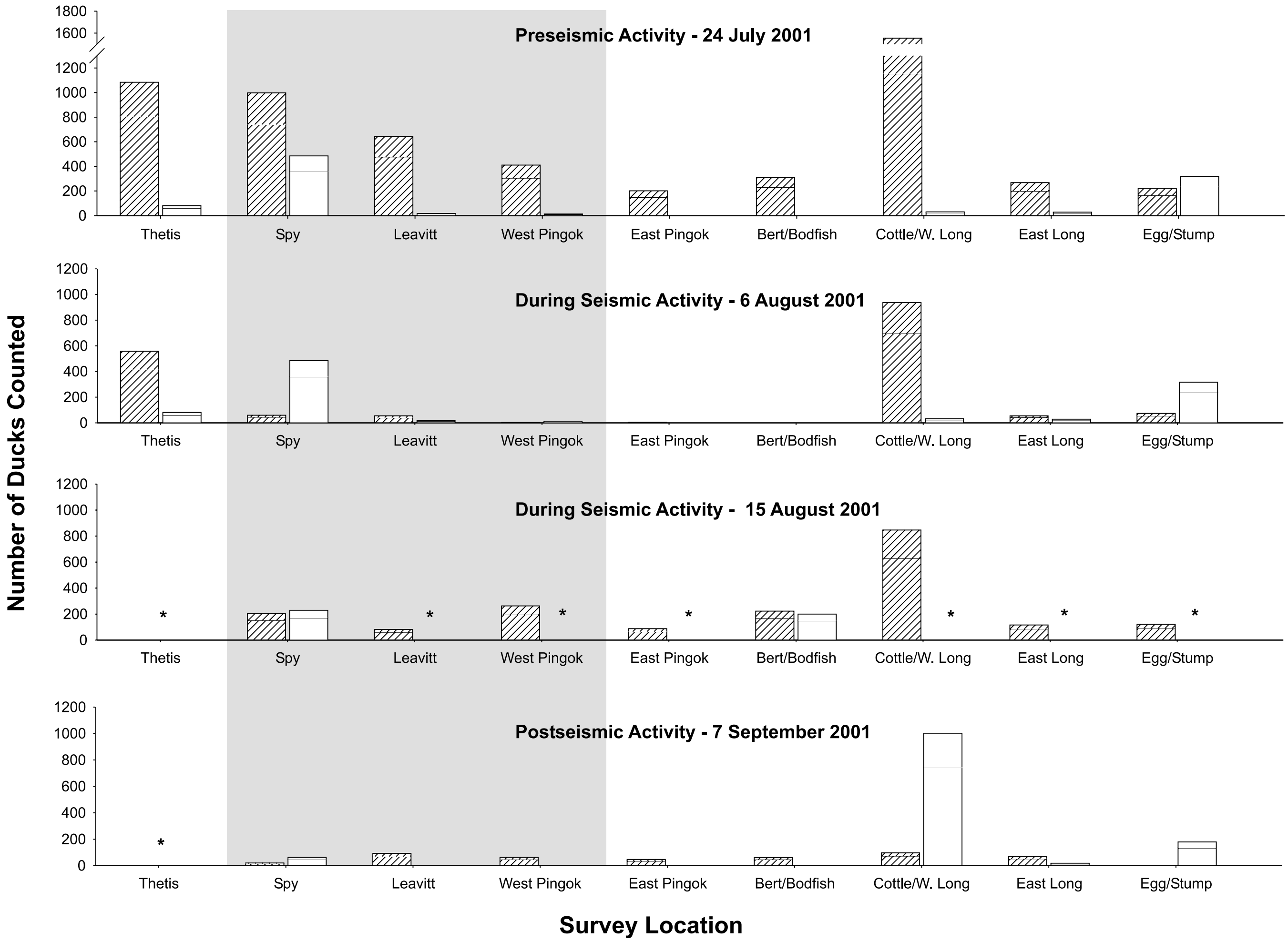
To examine changes in the proportion of ducks detected near DCCs within the seismic and control areas, we first computed the proportion of ducks present on a given day at each DCC site (observations were summarized for each 24-h period). We limited these calculations to ducks captured near a given DCC site. Next, we determined the cutoff dates for the preseismic, seismic, and postseismic periods. Because previous seismic studies indicated that the explosion of air guns was the most disturbing to wildlife (Richardson et al. 1995; Goold 1996), we considered 6–26 August to be the seismic period. This period encompassed all dates when air guns were used somewhere in the seismic treatment area. The days in which radio transmitters were monitored prior to 6 August and after 26 August were considered the preseismic and postseismic periods, respectively. Although we recognized that each DCC had different patterns of seismic activity exposure, the statistical analyses required us to standardize the seismic period to investigate changes occurring through the season at each DCC site. This allowed DCC sites to be used as replicates and contrasts could be generated between DCCs located within and outside of seismic areas. This standardization only applied to the five DCCs located in the seismic area, all of which were within 7 km of each other. Finally, we used a modified BACI (before–after control–impact) (Green 1979; McDonald et al. 2000) repeated-measures analysis of variance (ANOVA) (SAS procedure PROC MIXED) (SAS Institute Inc. 1996) to compare the difference in mean proportion of ducks in the seismic and control areas during the preseismic and seismic periods. This comparison was carried out as a single degree of freedom contrast (i.e., the BACI contrast) within the interaction effect of the repeated-measures ANOVA. Even though a few cells were missing data in the repeated measures analysis, the BACI contrast was always estimable. The null hypothesis of the BACI contrast was

$$H_0\colon \mu_{\mathrm{pc}} - \mu_{\mathrm{dc}} - \mu_{\mathrm{ps}} + \mu_{\mathrm{ds}} = 0$$

where μ_{pc} was the mean proportion of ducks in the preseismic period on the control area, μ_{dc} was the mean proportion of ducks in the seismic period on the control area, μ_{ps} was the mean proportion of ducks in the preseismic period on the seismic area, and μ_{ds} was the mean proportion of ducks in the seismic period on the seismic area. The alternative hypothesis was that the difference in preseismic and seismic proportions on the control area (i.e., $\mu_{\mathrm{pc}} - \mu_{\mathrm{dc}}$) was not equal to the difference in preseismic and seismic proportions in the seismic area (i.e., $\mu_{\mathrm{ps}} - \mu_{\mathrm{ds}}$). Prior to analyses, data were arcsine square-root transformed (i.e., $x_i = \arcsin(\sqrt{p_i})$ where p_i was the proportion of ducks in the area on day i) and plotted to ensure that the data met normality assumptions. We also accounted for autocorrelation in the daily transformed values by modeling the variance–covariance matrix with a power function that estimated correlations between observations from the same DCC. Modeling of the variance–covariance structure used the restricted maximum likelihood method (PROC MIXED documentation) (SAS Institute Inc. 1996). We assumed that observations from different DCCs were independent. Finally, from the repeated measures analysis and estimated variance–covariance matrix, we generated estimates of the proportion of ducks detected for each treatment (seismic and control areas and preseismic and seismic periods). Unfortunately, comparisons with the postseismic period were not possible, as ducks were beginning to fly by the time seismic activities ended, and several of our DCCs failed to work properly in the control areas at this time.

A similar analysis was conducted to investigate changes in the proportion of ducks diving on a daily basis near each DCC within the seismic and control areas. We developed an index to diving activity that controlled for diurnal variation in diving activity. Long-tailed Ducks dive to feed and previous studies have shown that ducks feed primarily during the day and roost at night (Flint et al. 2003). We determined the proportion of observations indicative of diving during each hour of each day for each DCC and then averaged these pro-

Fig. 2. Number of Long-tailed Ducks (*Clangula hyemalis*) counted from aircraft during the preseismic, seismic, and postseismic periods along the lagoon and ocean sides of barrier islands in the Beaufort Sea, Alaska, in 2001. Stacked bars represent observer counts (bottom portion of column) and corrected counts (top portion, see text for methods) and diagonally hatched and open bars represent lagoon and ocean counts, respectively. An asterisk indicates where surveys were not conducted on a given island because of weather. Islands where seismic activity occurred nearby are shaded gray.



portions across a 24-h period for each DCC. This approach controlled for diurnal variation and removed any weighting based on sample size that would have influenced a daily index. Although it would have been preferable to statistically investigate diving behavior during each hour of each day, this proved impossible because of compounded autocorrelation problems and large numbers of missing or sparsely populated cells. As above, data were arcsine square-root transformed, autocorrelation was accounted for, and estimates of diving proportions were determined. We used two-tailed tests and an alpha level of 0.05 in all cases.

Results

Aerial surveys

Long-tailed Ducks were observed near most of the islands during each of our surveys (Fig. 2). Particularly large concentrations of ducks occurred near Thetis, Spy, Cottle, and West Long islands. Most ducks were observed on the lagoon side of the barrier islands, although large numbers of ducks occurred on the ocean side of Spy, Cottle, and West Long islands during one or more of the surveys.

The total number of ducks detected (after correcting counts and standardizing data sets, see Methods and materials) during aerial surveys decreased from a high of 5499 during the first survey to 1981 during the second survey. The number of ducks decreased further to 1713 during the last survey. Although this pattern was consistent across islands within the seismic (Spy, Leavitt, West Pingok) and non-seismic areas (East Pingok to Stump islands), the magnitude of the change between the first and second surveys was much greater in the seismic area relative to the control area (24 July to 6 August counts: 89% vs. 42% decline). Both areas declined at a similar rate between the second and last surveys. When we restricted the aerial survey data to only the lagoon side of the barrier islands, a similar pattern was found.

Capture and location of radio-equipped Long-tailed Ducks

We trapped a total of 246 Long-tailed Ducks at five different sites; ducks were captured at one site within the seismic

Table 1. Number of Long-tailed Ducks (*Clangula hyemalis*) captured and radio-marked on barrier islands of the Beaufort Sea, Alaska, during 2001.

		Western control area		Eastern control area	
	Seismic area, Leavitt Island	Bertoncini Island	Cottle Island	Maguire Island	Flaxman Island
Number captured	30	9	1	124	82
Number (%) of males	29 (96.8)	9 (100)	1 (100)	124 (100)	70 (85.4)
Number radio-marked	29	9	1	31	32
Capture date(s)	30 July	29 July, 3 and 9 Aug.	1 Aug.	28 July	30 July

Table 2. Detection results for radio-equipped Long-tailed Ducks monitored by DCCs located on barrier islands and the mainland adjacent to the Beaufort Sea, Alaska, in 2001.

	Seismic area					Western control area		Eastern control area	
	F Pad	Oliktok Point	Pingok Island	East Spy Island	West Spy Island	Bodfish Island	Cottle Island	Maguire Island	Flaxman Island
Sampling (days)	35	31	28	34	32	28	13	16	18
Sampling (h)	659.2	659.2	621.3	730.8	654.4	649.7	228.7	343.7	321.8
No. of local radios monitored	29	29	29	29	29	10	10	32	31
Total no. of radios monitored	39	39	39	39	39	39	39	63	63
No. of local radios detected	6	3	28	28	15	10	5	27	27
No. of foreign radios detected	0	0	0	2	0	8	9	0	9
No. (mean ± SE) of fixes per radio	5.0±1.8	3.3±1.3	214.6±48.2	135.5±34.0	25.7±6.2	132.2±55.1	25.8±11.0	118.6±21.9	144.1±20.8
Range in no. of fixes per radio	1–11	2–6	4–995	2–699	1–99	4–737	2–160	2–395	2–446
Total fixes	30	10	6009	4066	386	2380	361	3202	5186

Note: “Local” radios refer to those placed on ducks at the capture site adjacent to the DCC and “foreign” radios refer to those placed on ducks at capture sites away from the DCC.

area and at two sites within each of the control areas (Fig. 1, Table 1). All ducks except seven at Bertoncini were caught prior to the start of seismic activities and most were males (94.7%, N = 246). A total of 102 male Long-tailed Ducks were equipped with radios throughout the five capture areas. Radio implementation was restricted to males, the predominant sex captured, to avoid any additional variation owing to a bird’s sex. Ducks captured at Bertoncini and Cottle islands were combined to represent ducks from the western control area because these locations were close to each other (within 4 km) and only one duck was captured at Cottle Island (Fig. 1). We did not combine ducks from the two capture areas in the eastern control area because the distance between the two sites was large (>12.7 km).

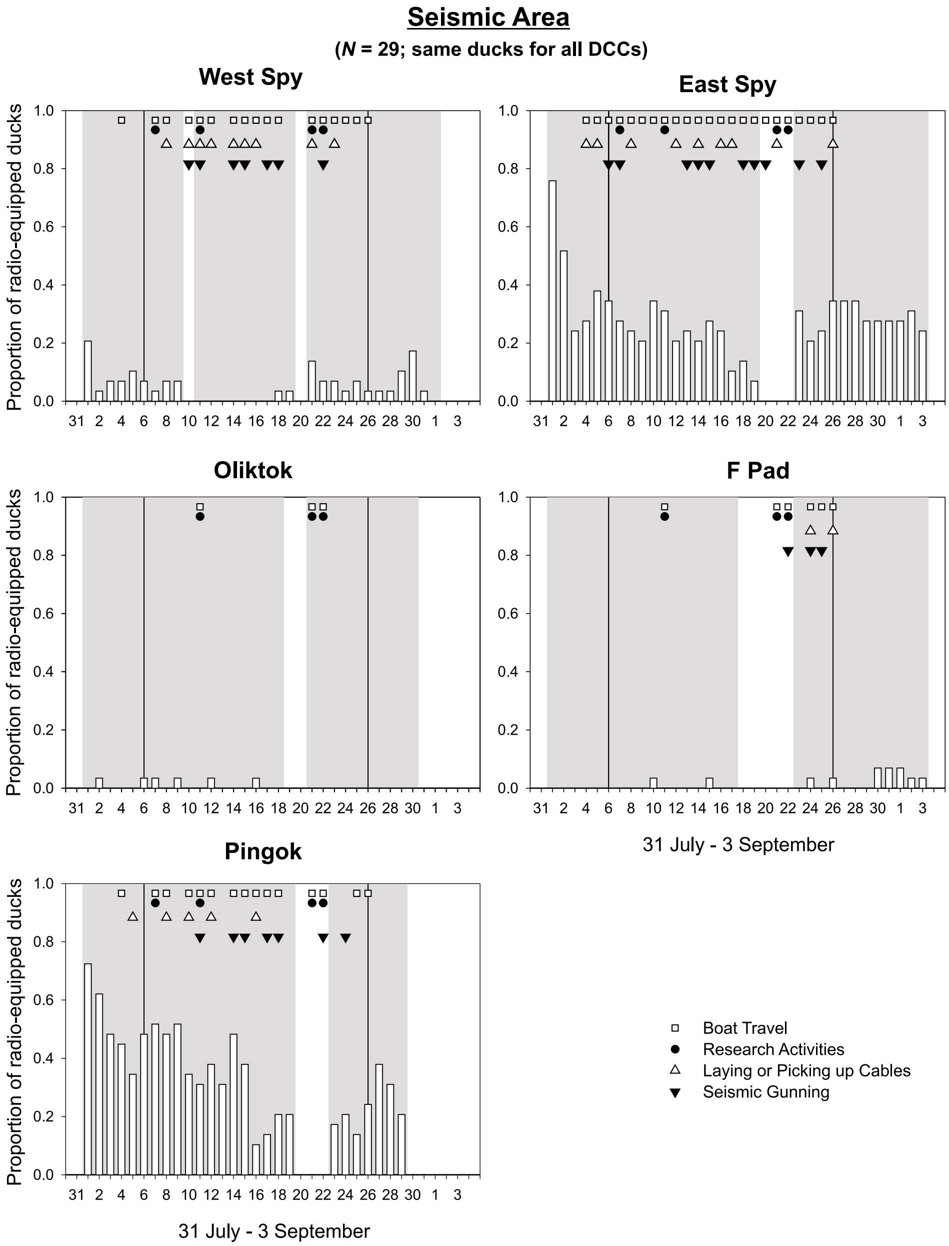
The DCCs began monitoring radio transmitters at some sites by 31 July, and all sites were active by 4 August (gray areas within Figs. 3 and 4). The first seismic boat moved west past Pingok Island on 4 August and cables were laid on the same day near the eastern half of Spy Island (see seismic activity symbols, Fig. 3). Air guns were fired for the first time on 6 August. Within the seismic area, radio transmitters were monitored for 5 days prior to the start of seismic activities, whereas in the two control areas, radio transmitters were monitored for 2–6 days prior to the start of air-gun activities in the seismic area. The seismic period lasted from 6 to 26 August (i.e., 21 consecutive days). Post monitoring was between 3 and 8 days in length depending on the DCC.

Each DCC collected data for 13–35 days (26.1 ± 8.3, mean ± SE) for a total of 4869 h of detection time during our study (Table 2). Of the initial sample of radio-equipped ducks, two (1.9%) may have died (i.e., mortality sensors were heard from an airplane but ducks were not found on the ground) and nine (8.8%) were not detected by any DCC after capture. All of these birds were from the eastern control area. The radio transmitters on the latter ducks may have failed or the ducks may have moved out of reception range. The high number of detections (i.e., fixes) per radio at DCCs located at Pingok, East Spy, Bodfish, Maguire, and Flaxman islands suggested that these sites were used heavily. In contrast, DCCs located at F Pad, Oliktok Point, West Spy Island, and Cottle Island had low-fix averages, indicating that the radio-equipped ducks seldom used these areas (although a few ducks were heard frequently even at these sites; Table 2).

Proportion of ducks detected and seismic activity effects

Of the five DCCs located in the seismic area, the highest proportion of ducks were detected at Pingok followed by East Spy, West Spy, F Pad, and Oliktok (Fig. 3). Only three

Fig. 3. Proportion of radio-equipped Long-tailed Ducks detected by the five DCCs located in the Seismic area, Beaufort Sea, Alaska, in 2001 (see Fig. 1 for location of DCCs). The proportion of radio-equipped ducks includes only those ducks originally captured in the seismic area. The gray shading indicates when the DCCs were recording data. The vertical lines represent the first and last days when seismic activity occurred in the general area. The five symbols represent the types of activities occurring within a 2.5-km radius of each DCC.

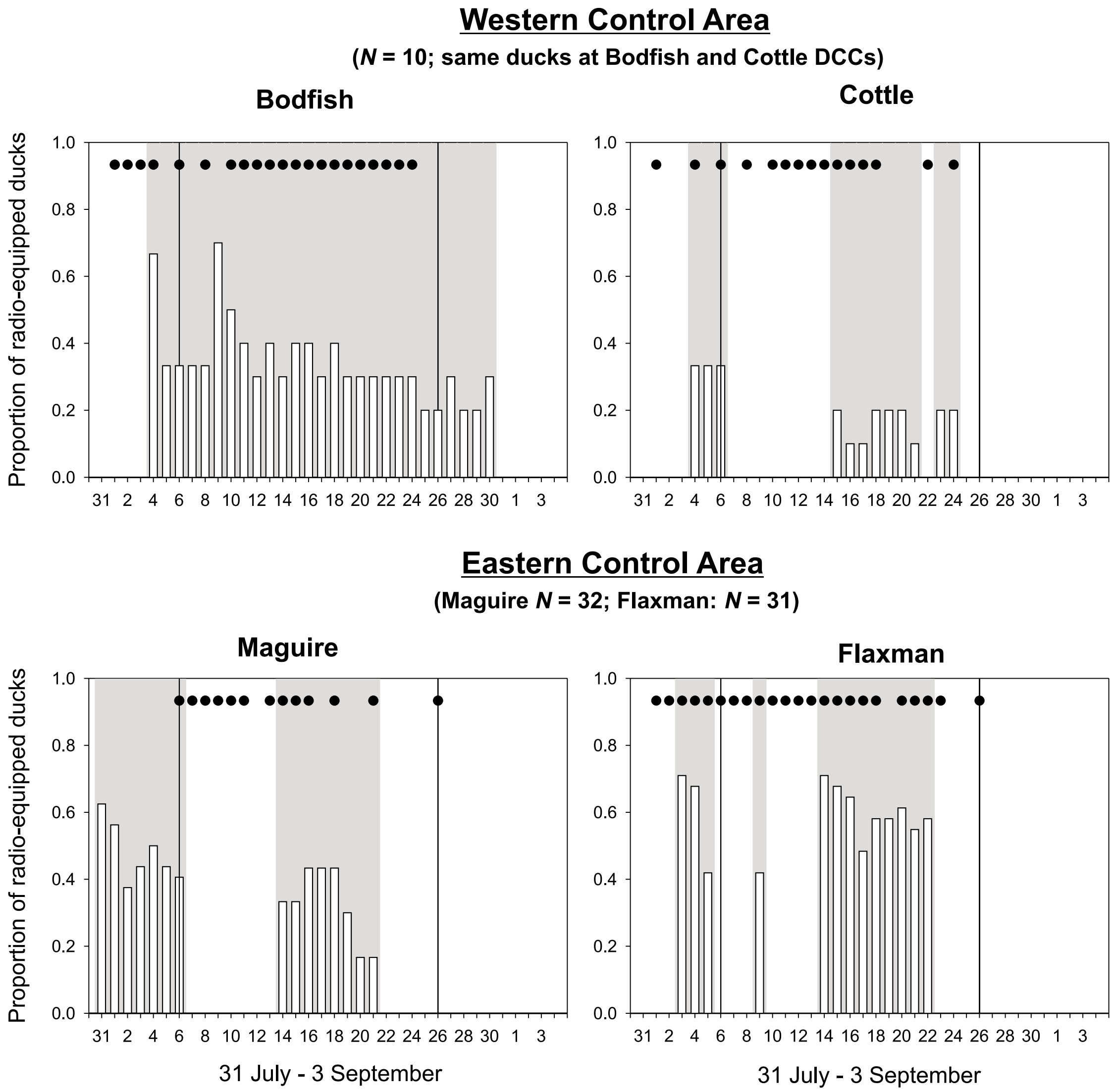


and six radios were detected at the Oliktok and F Pad DCC sites, respectively, indicating that few radio-equipped Long-tailed Ducks moved to the mainland from the barrier islands within the seismic area. These two DCCs were excluded from subsequent statistical analyses because of their low detection rate. In the western control area, the Bodfish DCC detected most of the radios (Fig. 3). The Cottle DCC site detected less than 40% of the 10 radios placed on birds in that area. This disparity coincides with where ducks were captured (Table 1). In the eastern control area, generally over 40% of the radio-equipped ducks were detected each day, and the detection rate remained relatively constant through time (Fig. 4).

Table 3. Repeated-measures analysis of variance (ANOVA) for proportion of Long-tailed Ducks detected by three and four DCCs located in the seismic and control areas, respectively.

Source of variation	Numerator df	Type III *F*	Pr >*F*
Seismic	1	3.07	0.140
Date	25	1.92	0.017
Seismic × date	23	1.23	0.249
Contrast: BACI-seismic × period	1	0.01	0.939

Fig. 4. Proportion of radio-equipped Long-tailed Ducks detected by the four DCCs located in the western and eastern control areas, Beaufort Sea, Alaska, in 2001. In the western control area, the proportion of radio-equipped ducks included all those captured near both the Bodfish Island and Cottle Island DCCs. In the eastern control area, the proportion of radio-equipped ducks included only those captured near their corresponding DCC site. The gray shading indicates when the DCCs were recording data. The vertical lines represent the first and last days when seismic activity occurred in the seismic area. The ● symbol represents when research boats were within a 2.5-km radius of each DCC.



A repeated-measures ANOVA indicated that there were no significant differences in the proportion of Long-tailed Ducks detected by DCCs located in seismic and control areas (seismic main effect, Table 3). There was a significant date effect, suggesting that the proportion of ducks declined through the molting season (date main effect, Table 3). However, the primary effect of interest was not significant (P = 0.94, BACI contrast, Table 3), indicating that the difference in proportion of ducks staying near each DCC for the preseismic and seismic periods was nearly identical in the control and seismic areas. Estimates of the proportion of ducks indicated that the preseismic period in the control areas had the highest average proportion of ducks (mean and 95% confidence interval (CI) across days = 0.54 and 0.33–0.75, N = 13) followed by the seismic period in the control areas (0.34 and 0.20–0.49, N = 49), by the preseismic period in the seismic area (0.33 and 0.15–0.54, N = 15), and finally by the seismic period in the seismic area (0.16 and 0.05–0.31, N = 51).

Diving indices and seismic activity effects

Our index of diving intensity varied among DCC sites (Figs. 5 and 6). DCCs located at East Spy, Pingok, and Maguire islands detected exceptionally high indices of diving ducks (60%–80%), whereas the West Spy DCC had low indices (20%).

The repeated-measures ANOVA that we used to examine variation in diving indices also failed to find significant differences between seismic and control areas (seismic main effect, Table 4), through the season (date main effect, Table 4), or in the slope through time on the seismic and control areas (seismic × date effect, Table 4). The BACI contrast was also

Fig. 5. Diving indices of Long-tailed Ducks for three DCCs (West and East Spy and Pingok) placed within the seismic area of the Beaufort Sea, Alaska, in 2001. Indices reflect only ducks originally captured in the seismic area. The gray shading indicates when the DCCs were recording data. The vertical lines represent the first and last days when seismic activity occurred in the general area. The five symbols represent when and the types of activities occurring within a 2.5-km radius of each DCC.

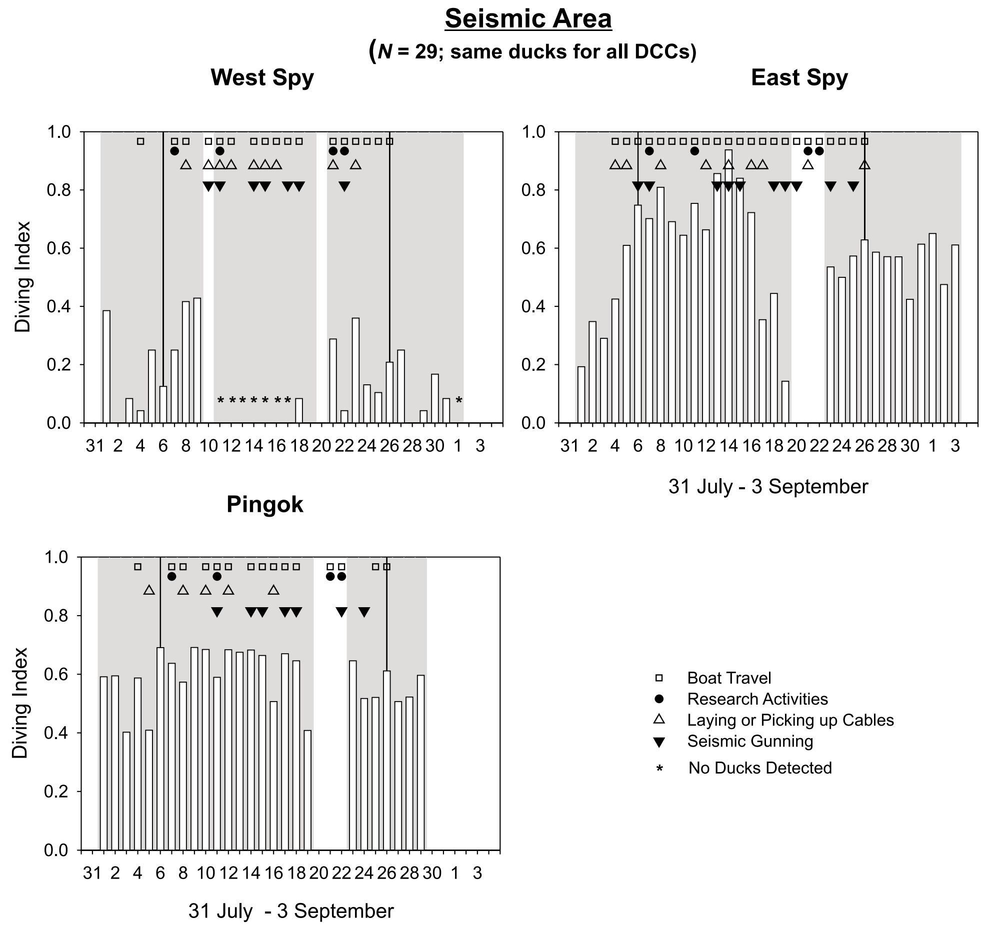


Table 4. Repeated-measures ANOVA for proportion of Long-tailed Ducks diving when detected by three and four DCCs located in the seismic and control areas, respectively.

Source of variation	Numerator df	Type III *F*	Pr >*F*
Seismic	1	0.62	0.468
Date	25	0.84	0.677
Seismic × date	23	1.25	0.233
Contrast: BACI-seismic × period	1	0.05	0.829

not significant (P = 0.83, BACI contrast, Table 4), indicating that the difference in diving indices near each DCC between the preseismic and seismic periods were nearly identical in the control and seismic areas. Estimates of the diving indices suggested that the highest proportions were in the seismic period in the control areas (mean and 95% CI across days = 0.50 and 0.31–0.70, N = 49) followed by the preseismic period in the control areas (0.46 and 0.17–0.76, N = 13), by the seismic period in the seismic area (0.42 and 0.22–0.63, N = 51), and finally by the preseismic period in the seismic area (0.32 and 0.09–0.61, N = 15).

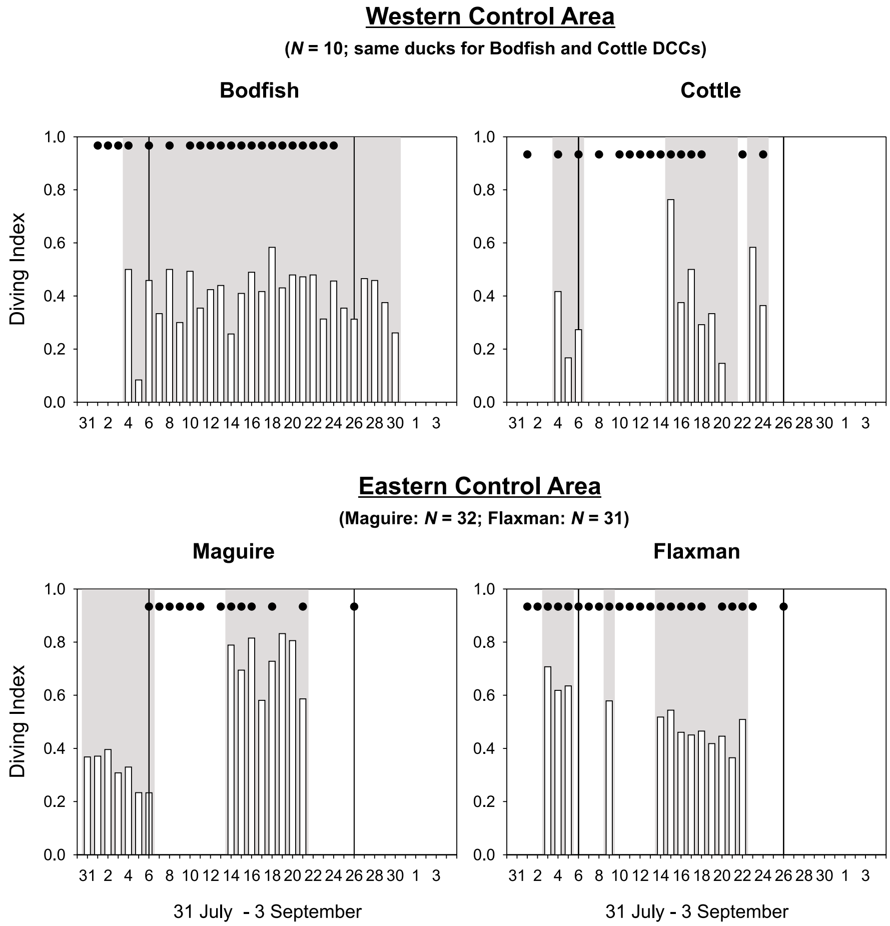
Movement of ducks

The DCCs located at East Spy, Bodfish, Cottle, and Flaxman islands detected between two and nine radio-equipped ducks that had been caught at adjacent capture sites (Figs. 7 and 8). In all but the East Spy DCC, this represented ducks moving east away from their original capture site. This easterly movement of radio-equipped ducks occurred during the middle (e.g., loss of ducks captured near East Spy, Pingok, and Maguire DCCs and increase in ducks from other capture areas at the Bodfish, Cottle, and Flaxman DCCs; Figs. 7 and 8) and end of seismic activities (e.g., increase in ducks from other capture areas at East Spy and Bodfish DCCs; Figs. 7 and 8). Easterly movement of this sort, if restricted to the seismic area, would support the hypothesis that ducks were moving away from the seismic activities. However, this movement was observed in both the seismic and control areas. Further, we also documented local ducks returning to their initial capture areas before seismic activities had ceased (e.g., West Spy, East Spy, and Pingok DCCs).

Discussion

Both aerial surveys and DCC data indicated that the proportion of ducks detected in both the seismic and control ar-

Fig. 6. Diving indices of Long-tailed Ducks for the four DCCs located in the western and eastern control areas of the Beaufort Sea, Alaska, in 2001. In the western control area, the number of ducks included all those captured near both the Bodfish Island and Cottle Island DCCs. In the eastern control area, the number of ducks included those captured near the corresponding DCC. The gray shading indicates when the DCCs were recording data. The vertical lines represent the first and last days when seismic activity occurred in the seismic area. The ● symbol represents when research boats were within a 2.5-km radius of each DCC.

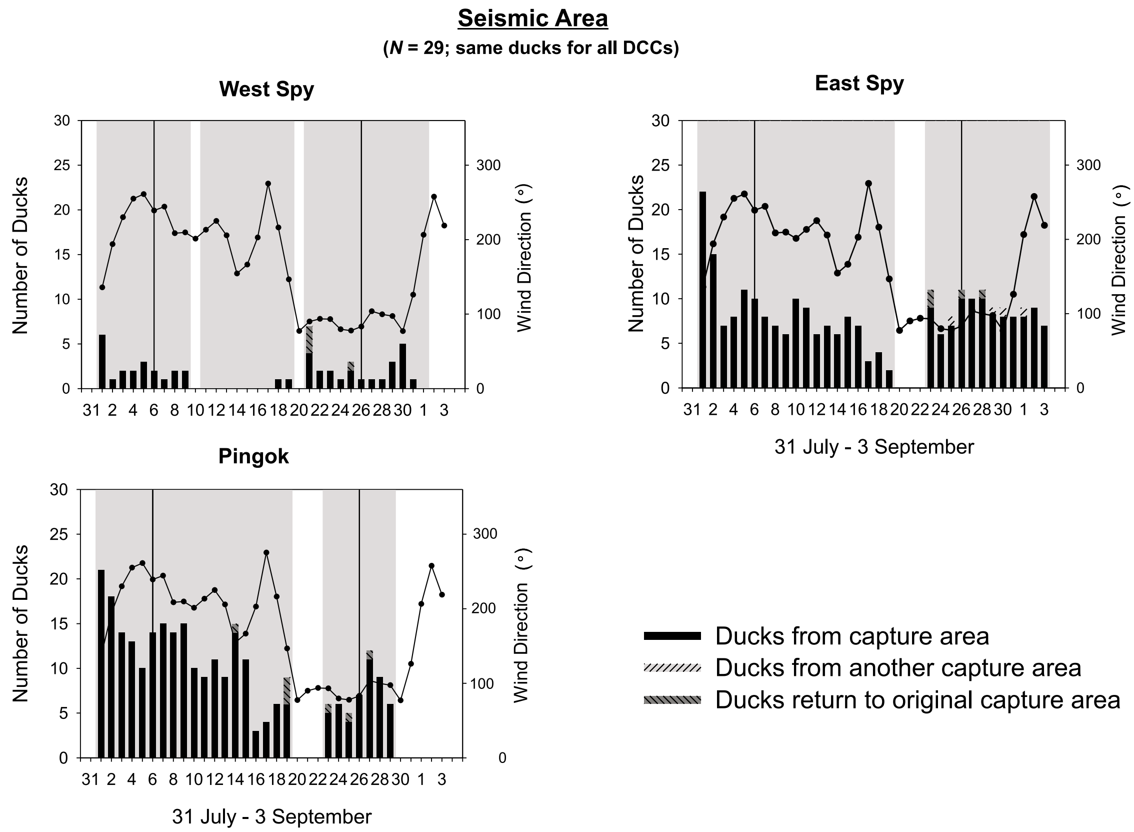


eas changed similarly following the start of seismic activity. Indeed, an analysis based on a modified BACI approach (McDonald et al. 2000) found that the difference in proportion of ducks staying near each DCC in the preseismic and seismic periods was nearly identical in the control and seismic areas. Unfortunately, we could not conduct a similar analysis on aerial survey counts and interlagoon movements because replicate data were not available. Nonetheless, changes in aerial survey counts and lagoon movements of ducks were similar in the seismic and control areas, suggesting that other factors were affecting duck numbers and distribution. The highest proportion of ducks was recorded during the preseismic period, with fewer ducks detected during the seismic and postseismic periods.

If there was an effect of underwater seismic activity on Long-tailed Ducks, the magnitude may not have been great enough to be detected by the methods employed in this study. DCCs, while enabling us to collect data continuously over a very large area, are only capable of recording the presence of ducks within a 2.5-km radius. Short-distance movements of Long-tailed Ducks, as would occur in response to a passing vessel, would not be detected. Further, we did not directly observe the behavior of Long-tailed Ducks in or outside the seismic area. Johnson (1982) documented Long-tailed Ducks moving from one habitat to another in response to aircraft, boat, and human disturbances. We know from direct observations of ducks near our research vessels (12- to 18-ft (1 ft = 0.3048 m) rubber or aluminum boats) that ducks frequently dive and swim away short distances. However, we typically traveled through an area quickly, allowing them to resurface and return to their previous location. Whether slow-moving boats and loud airgun pulses affect Long-tailed Ducks similarly is unknown.

Several other statistical and ecological factors may have reduced our ability to detect any effects from seismic activity. First, our study may have lacked statistical power to detect differences between seismic and control areas. We would likely need additional seismic areas and associated controls to compensate for site variation. Unfortunately, the cost of conducting underwater seismic surveys and monitoring radio-equipped ducks prohibits such a design. Second, our design suffered from having treatment periods of unequal duration. The preseismic period was rather short and the seismic period was relatively long. This could not be controlled because there is a limited window in which seismic testing can be conducted (owing to sea ice along the coast) and it overlaps substantially with the molting period of Long-tailed Ducks. The long seismic activity period pre-

Fig. 7. Number of radio-equipped Long-tailed Ducks detected by three DCCs located on barrier islands within the seismic area of the Beaufort Sea, Alaska, in 2001. Black bars represent detections of ducks originally equipped with radio transmitters near the DCCs, light gray bars represent those ducks detected that were captured away from the DCCs, and dark gray bars represent ducks that returned after having departed the area. The gray background shading indicates when the DCCs were recording data. The vertical lines represent the first and last days when seismic activity occurred in the general area. Wind direction is represented in a line and scatter plot.

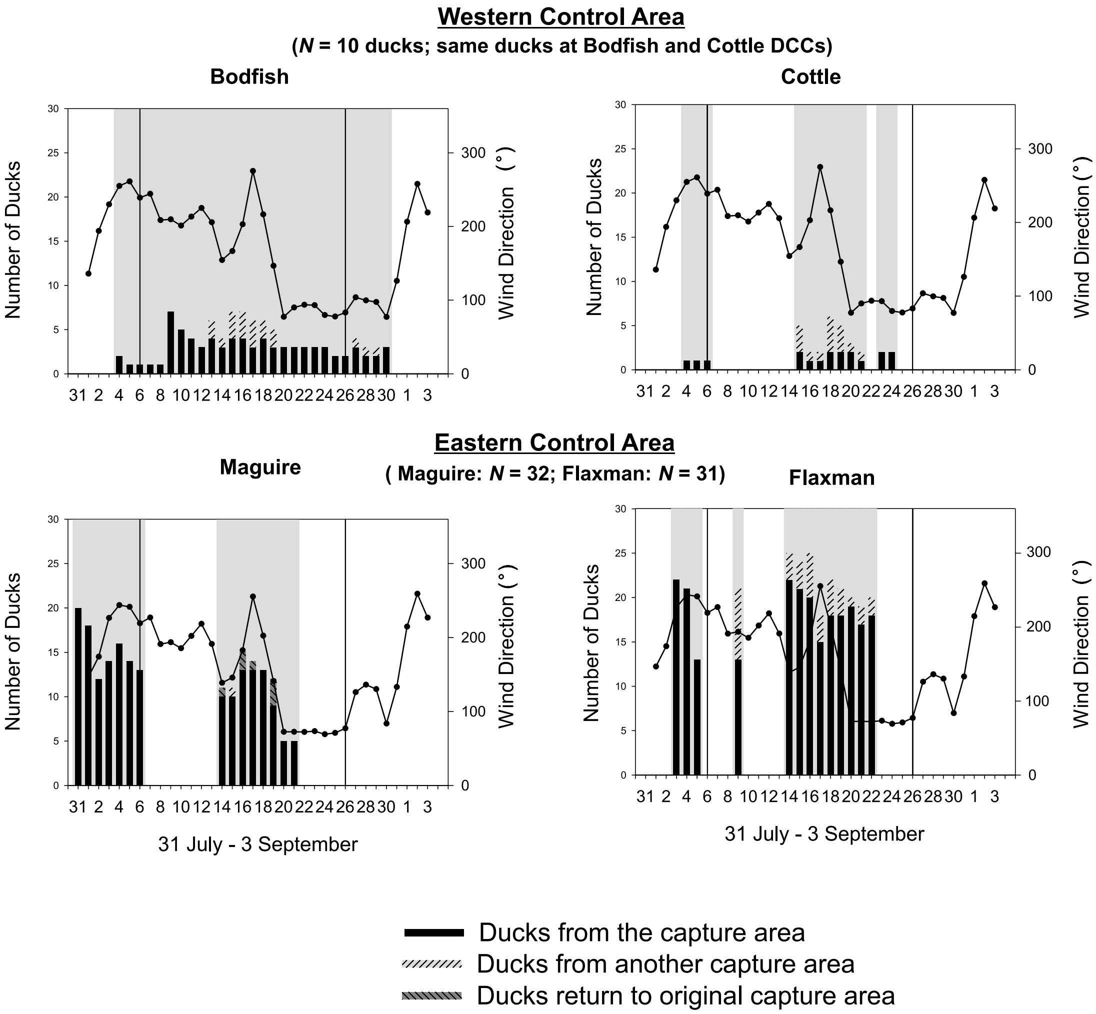


cluded comparisons with the postseismic period because many ducks were completing their molt and beginning to fly. Other researchers have reported Long-tailed Ducks flying in large numbers during late August and leaving the lagoons for the ocean environment (Johnson and Richardson 1982; Bartels et al. 1984; Brackney et al. 1985; Fischer et al. 2002).

Other factors besides seismic activity may have affected Long-tailed Duck movements and distribution. Consistently strong southwest winds (averaging between 4 and 9 m/s) during much of the preseismic and seismic periods of our study likely caused some birds to move east (out of the seismic area) (Figs. 7 and 8). These winds corresponded with a decrease in duck numbers. Islands located in the seismic area are especially exposed to southwesterly winds (Fig. 1), and thus any ducks residing in the area might be expected to ride the waves east. An abrupt shift in wind direction from the east during 20–30 August (Figs. 7 and 8) also coincided with duck numbers either stabilizing or increasing in the seismic area (e.g., East and West Spy and Pingok, Fig. 7). Other factors that may affect duck distribution and abundance are seasonal shifts in prey distribution and abundance, lagoon orientation and configuration, bottom configuration, and other weather-related phenomena (Griffiths and Dillinger 1981; Bartels and Doyle 1984; Noel et al. 2001; Fischer et al. 2002). Other studies have shown that radio-equipped Long-tailed Ducks typically remained within the same lagoon system throughout their 2- to 3-week molt period (Bartels et al. 1984; Brackney et al. 1985), although low sample size and potential negative impacts of radio harnesses may make these results unreliable.

Contrary to our prediction, seismic activity did not significantly change the diving intensity of Long-tailed Ducks. Indeed, the difference in diving intensity near each DCC between the preseismic and seismic periods was nearly identical in the seismic and control areas. Interestingly, the diving intensity of Long-tailed Ducks was higher at some DCC sites (e.g., East Spy, Pingok, and Maguire; Figs. 5 and 6). The reason for this is unclear. Because Long-tailed Ducks dive to feed, it is possible that prey levels are higher in these areas and ducks were simply diving more to access this prey base. The higher diving rates near the East Spy and Pingok DCCs may or may not be related to the seismic activity. Behavioral observations of Long-tailed Ducks are needed to better understand how individual ducks respond to air-gun pulses. For example, Long-tailed Ducks may dive less to avoid the underwater sounds or dive more to avoid disturbances associated with the vessels (i.e., escape behavior). Further, seismic pulses may also affect Long-tailed Duck prey, possibly driving them into the water column or onto the surface of the seabed, making them easier for ducks to find. This might result in higher diving intensities.

Fig. 8. Number of radio-equipped Long-tailed Ducks detected by four DCCs located on the barrier islands within the eastern and western control areas of the Beaufort Sea, Alaska, in 2001. Black bars represent detections of ducks originally equipped with radio transmitters near the DCCs, light gray bars represent those ducks detected that were captured away from the DCCs, and dark gray bars represent ducks that returned after having departed the area. The gray background shading indicates when the DCCs were recording data. The vertical lines represent the first and last days when seismic activity occurred in the general area. Wind direction is represented in a line and scatter plot.



Effects of seismic activities on other animals

Although extensive field studies on the effects of seismic activity on marine mammals and fish have been conducted (e.g., Richardson et al. 1995; McCauley et al. 2000), very little information on birds is available. Stemp (1985) failed to document any effect of seismic activities on seabirds, although these data were confounded by seasonal changes in bird numbers in relation to migration. Stemp (1985) insisted that these results not be extrapolated to areas with large concentrations of feeding or migrating birds or birds that are molting. Most studies of marine mammals have documented general avoidance or behavioral changes, although the overall reaction depends on the species, the strength of the seismic pulses, and whether animals are attracted to an area for feeding or reproduction (Richardson et al. 1986, 1995; Goold 1996; Richardson 2001). Given the variable reaction of mammals to seismic activity, it is clear that additional studies on other species of birds are needed to fully understand the effects of underwater seismic testing.

Conclusions

Although this study did not identify a clear response of Long-tailed Ducks to seismic activities, that does not mean that this species is unaffected by seismic activities. Seismic activities may affect Long-tailed Ducks in different ways or in a manner too subtle to be detected with the sampling methods and effort that we used. With this in mind, the potential for the occurrence of unknown impacts should be considered when seismic work is planned, and molting Long-tailed Ducks should be avoided altogether when this can be done without unduly sacrificing other aspects of seismic operations and without causing impacts to other animals. Potential options include winter seismic surveys or open-water surveys immediately after breakup of sea ice.

Acknowledgments

Eric Taylor, Bill Streever, and Dave Trudgen are especially thanked for approaching us to conduct the study and helping with the design. G. Spencer, J. Benson, A. Brelsford, S. Conlon, P. Flint, L. Galati, B. Gamble, R. Inman, M. Petersen, M. Stafford, J. Storey, S. Stroka, E. Sussman, C. Van Hemert, and H. Wilson provided field assistance. John Sarvis, Eric Akola, and Garland Dobson piloted the aircraft in a safe and efficient manner. We also thank Mike Barker and the ExxonMobil Production Company for allowing us to use their ATCO trailer on Flaxman Island and assisting us in transporting fuel. The people at Milne Production Facility and Alaska Clean Seas provided support to our field camps. Western Geophysical, especially Kurt Kinden, provided detailed information on seismic activities throughout the project. Dirk Derksen, Paul Flint, Margaret Petersen, Jean-Pierre Savard, Bill Streever, and an anonymous reviewer provided constructive comments on earlier drafts of the manuscript. BP Exploration (Alaska) Inc., the U.S. Geological Survey, and the U.S. Fish and Wildlife Service provided funding and logistical support for this project.

References

Ankney, C.D. 1979. Does the wing molt cause nutritional stress in lesser snow geese? Auk, **96**: 68–72.

Bartels, R.F., and Doyle, T.J. 1984. Migratory bird use of the coastal lagoon system of the Beaufort Sea coastline within the Arctic National Wildlife Refuge, Alaska, 1983. *In* 1983 update report of the baseline study. *Edited by* G.W. Garner and P.E. Reynolds. U.S. Fish and Wildlife Service, Fairbanks, Alaska. pp. 169–199.

Bartels, R.F., Doyle, T.J., and Wilmers, T.J. 1984. Movement of molting Oldsquaw within the Beaufort Sea coastal lagoons of Arctic National Wildlife Refuge, Alaska, 1983. *In* 1983 update report of the baseline study. *Edited by* G.W. Garner and P.E. Reynolds. U.S. Fish and Wildlife Service, Fairbanks, Alaska. pp. 156–168.

Brackney, A.W., Morton, J.M., Noll, J.N., and Masteller, M.A. 1985. Movement of molting oldsquaw within the Beaufort Sea coastal lagoons of the Arctic National Wildlife Refuge, Alaska, 1984. Arctic National Wildlife Refuge Progress Report No. FY85-12, U.S. Fish and Wildlife Service, Fairbanks, Alaska.

Craig, P.C., Griffiths, W.B., Johnson, S.R., and Schell, D.M. 1984. Trophic dynamics in an Arctic lagoon. *In* The Alaskan Beaufort Sea: ecosystems and environments. *Edited by* P.W. Barnes, D.M. Schell, and E. Reimnitz. Academic Press, Orlando, Fla. pp. 347–380.

Fischer, J.B., Tiplady, T.J., and Larned, W.W. 2002. Monitoring Beaufort Sea waterfowl and marine birds, aerial survey component. Minerals Management Service Report 2002-002, U.S. Fish and Wildlife Service, Division of Migratory Bird Management, Anchorage, Alaska.

Flint, P.L., Reed, J.A., Franson, J.C., Hollmén, T.E., Grand, J.B., Howell, M.D., Lanctot, R.B., Lacroix, D.L., and Dau, C.P. 2003. Monitoring Beaufort Sea waterfowl and marine birds. OCS Study, Minerals Management Service Report 2003-037, U.S. Geological Survey, Alaska Science Center, Anchorage, Alaska.

Gilders, M.A., and Cronin, M.A. 2000. North Slope oil field development. *In* The natural history of an Arctic oil field: development and the biota. *Edited by* J.C. Truett and S.R. Johnson. Academic Press, San Diego, Calif. pp. 15–33.

Goold, J.C. 1996. Acoustic assessment of populations of common dolphin *Delphinus delphis* in conjunction with seismic surveying. J. Mar. Biol. Assoc. U.K. **76**: 811–820.

Goudie, R.I., and Ankney, C.D. 1986. Body size, activity budgets, and diets of sea ducks wintering in Newfoundland. Ecology, **67**: 1475–1482.

Green, R.H. 1979. Sampling design and statistical methods for environmental biologists. Wiley, New York.

Greene, C.R., Jr., and Richardson, W.J. 1988. Characteristics of marine seismic survey sounds in the Beaufort Sea. J. Acoust. Soc. Am. **83**: 2246–2254.

Griffiths, W.B., and Dillinger, R.E. 1981. Beaufort Sea barrier island–lagoon ecological process studies: final report, Simpson Lagoon. Part 5. Invertebrates. *In* Environmental assessment of the Alaskan continental shelf, final reports of principal investigators. Vol. 8. National Oceanic and Atmospheric Administration, Boulder, Colo. pp. vi–198.

Hohman, W.L., Ankney, C.D., and Gordon, D.H. 1992. Ecology and management of postbreeding waterfowl. *In* Ecology and management of breeding waterfowl. *Edited by* B.D.J. Batt, A.D. Afton, M.G. Anderson, C.D. Ankney, D.H. Johnson, J.A. Kadlec, and G.L. Krapu. University of Minnesota Press, Minneapolis, Minn. pp. 128–189.

Howell, M.D. 2002. Molting dynamics of male Long-tailed Ducks on the Beaufort Sea. M.S. thesis, Auburn University, Auburn, Ala.

Johnson, S.R. 1982. Continuing investigations of Oldsquaws (*Clangula hyemalis* L.) during the molt period in the Alaskan Beaufort Sea. *In* Environmental Assessment of Alaskan Continental Shelf, final report. Vol. 23. NTSI PB 85-212595/AS, Bureau of Land Management / National Oceanic and Atmospheric Administration, Outer Continental Shelf Environmental Assessment, Juneau, Alaska. pp. 547–563.

Johnson, S.R. 1984. Habitat use and behavior of nesting common eiders and molting oldsquaws at Thetis Island, Alaska, during a period of industrial activity. Report by LGL Alaska Research Associates, Inc., for Sohio Alaska Petroleum Company, Anchorage, Alaska.

Johnson, S.R., and Gazey, W.J. 1992. Design and testing of monitoring program for Beaufort Sea waterfowl and marine birds. OCS Study, Minerals Management Service Report 92-0060 by LGL Alaska Research Associates, Inc., for United States Minerals Management Service, Herndon, Va.

Johnson, S.R., and Richardson, W.J. 1982. Waterbird migration near the Yukon and Alaskan coast of the Beaufort Sea: II. Moult migration of seaducks in summer. Arctic, **35**: 291–301.

McCauley, R.D., Fewtrell, J., Duncan, A.J., Jenner, C., Jenner, M.-N., Penrose, J.D., Prince, R.I.T., Adhitya, A., Murdoch, J., and McCabe, K. 2000. Marine seismic surveys — a study of environmental implications. APPEA J. 2000: 692–708.

McDonald, T.L., Erickson, W.P., and McDonald, L.L. 2000. Analysis of count data from before–after control–impact studies. J. Agric. Biol. Environ. Stat. **5**: 262–279.

Murphy, M.E., and King, J.R. 1982. Amino acid composition of the plumage of the white-crowned sparrow. Condor, **84**: 435–438.

Noel, L.E., Johnson, S.R., and Rodrigues, R. 2001. Aerial surveys of molting waterfowl in the barrier island–lagoon systems between Spy Island and Brownlow Point, Alaska, 2000. Report by LGL Alaska Research Associates, Inc., for BP Exploration (Alaska) Inc., Anchorage, Alaska.

Pietz, P.J., Brandt, D.A., Krapu, G.L., and Buhl, D.A. 1995. Modified transmitter attachment for adult ducks. J. Field Ornithol. **66**: 408–417.

Richardson, W.J. 2001. Marine mammal and acoustical monitoring of Western Geophysical's open-water seismic program in the Alaskan Beaufort Sea, 2001: 90-day report. Report TA2564-3 by LGL Limited environmental research associates for Western Geophysical LLC, Anchorage, Alaska, and National Marine Fisheries Service, Anchorage, Alaska, and Silver Spring, Md.

Richardson, W.J., Würsing, B., and Greene, C.R., Jr. 1986. Reactions of bowhead whales, *Balaena mysticetus*, to seismic exploration in the Canadian Beaufort Sea. J. Acoust. Soc. Am. **79**: 1117–1128.

Richardson, W.J., Greene, C.R., Jr., Malme, C.I., and Thomson, D.H. 1995. Marine mammals and noise. Academic Press, San Diego, Calif.

SAS Institute Inc. 1996. SAS/STAT software: changes and enhancements through release 6.11 [computer program]. SAS Institute Inc., Cary, N.C.

Stemp, R. 1985. Observations on the effects of seismic exploration on seabirds. *In* Proceedings of the Workshop on the Effects of Explosives Use in the Marine Environment, 29–31 January 1985. *Edited by* G.D. Greene, F.R. Engelhardt, and R.J. Paterson. Tech. Rep. 5, Canada Oil and Gas Lands Administration, Environmental Protection Branch, Ottawa, Ont. pp. 217–231.

United States Army Corps of Engineers. 1999. Final environmental impact statement. Beaufort Sea Oil and Gas Development/Northstar Project, United States Army Corps of Engineers, Anchorage, Alaska.

Wilbor, S.L. 1999. Status report on the Bering/Pacific Oldsquaw (*Clangula hyemalis*) population. The Alaska Natural Heritage Program, Environment and Natural Resources Institute, University of Alaska, Anchorage, Alaska.