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ACOUSTIC EFFECTS OF OIL PRODUCTION ACTIVITIES ON BOWHEAD AND WHITE WHALES VISIBLE DURING SPRING MIGRATION NEAR PT. BARROW, ALASKA--1990 PHASE:

SOUND PROPAGATION AND WHALE RESPONSES TO PLAYBACKS OF CONTINUOUS DRILLING NOISE FROM AN ICE PLATFORM, AS STUDIED IN PACK ICE CONDITIONS

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PROJECT ORGANIZATION

The 1990 phase of this contract was conducted by LGL Ltd., environmental research associates, assisted by subcontractor Greeneridge Sciences Inc. **LGL** organized the project as a whole, and conducted the biological aspects of the work. M. Smultea and B. Würsig of the Marine Mammal Research Program, Texas A & M University, worked with LGL on the biological components. **Greeneridge** was responsible for the physical acoustics components. The affiliations of the senior authors (in boldface) and co-authors are as follows:

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TABLE OF CONTENTS

EXECUTIVE SUMMARY

Previous studies of the reactions of bowhead whales to noise from oil industry operations have all been conducted during late summer or early autumn, in open water or at most light ice conditions. Concern has arisen about potential reactions of bowheads to man-made noise in the leads through which bowheads migrate in spring. Particular concern has arisen about the possible effects of continuous noise from structures that might be used for oil production in or near spring lead systems.

Objectives

General Objectives

In response to this concern, the Minerals Management Service funded the present experimental study of the effects of noise from oil production activities on bowhead and (secondarily) white whales during their spring migrations around Alaska. The overall objectives of the study can be summarized as

1. To quantify sound transmission loss and ambient noise within nearshore leads off northern Alaska in spring, emphasizing propagation of underwater sounds produced by production platforms and icebreakers.
2. To quantify the short term behavioral responses of spring-migrating bowhead whales and, if possible, white whales to sounds from production platforms and icebreakers.
3. To assist and coordinate with other studies and local resource users to maximize collection of needed data and avoid conflict with subsistence whaling activities.
4. To analyze the data in order to test hypotheses concerning the effects of oil industry noises on the movement patterns and behavior of bowhead and white whales.

Specific 1990 Objectives

The specific objectives of the 1989 and 1990 phases of this project were similar. Because of the poor weather and ice conditions in 1989, and the low number of whales accessible in that year, the data on reactions to drilling platform sounds acquired in 1989 were too sparse to be conclusive. Hence, the highest priority during the 1990 field program, as in 1989, was to study the reactions of bowheads to noise from a bottom-founded drilling or production platform. When possible, reactions of white whales to this sound were to be determined as well. Underwater playback techniques were to be used to simulate the noise from an actual platform. As a lower priority, the reactions of bowheads and white whales to actual helicopter overflights were to be determined if opportunities allowed. Because of concern about the effects of low-frequency industrial sound components on bowheads, and the inability of a practical sound projector to reproduce those components, several indirect methods of addressing the importance of low frequency components were identified as objectives in 1990.

The specific objectives for the second field season, in 1990, were as follows:

1. To measure ambient noise levels and characteristics in leads and cracks along the spring migration corridor of bowhead and white whales in the western Beaufort

Sea, including infrasonic components. [Infrasounds are sounds at frequencies less than the lower limit of human hearing, generally taken to be 20 Hz.]

2. To measure and model transmission loss of underwater sound along that part of the spring migration corridor, based on playbacks of (a) test tones at selected frequencies between 50 Hz and 10 kHz, and (b) continuous drilling platform sound (*Karluk* sounds).
3. To measure the short-term behavioral responses of bowheads and (as possible) white whales visible in open water areas along their spring migration corridor in the western Beaufort Sea to underwater playbacks of continuous drilling platform sound (*Karluk* and CIDS sounds).
4. To collect some of the data needed to assess the importance of the infrasonic components (<20 Hz) of industrial noise; specifically, to measure ambient noise at infrasonic frequencies, and determine whether bowhead calls contain infrasonic components.
5. To measure the short-term behavioral responses of bowheads and (as possible) white whales visible in open water areas along their spring migration corridor in the western Beaufort Sea to actual helicopter overflights.
6. To document, as opportunities allow, other aspects of the movements, behavior, basic biology, disturbance responses and acoustic environment of bowheads and white whales along their spring migration corridor in the western Beaufort Sea.
7. To assist and coordinate with other studies and local resource users to maximize collection of needed data and to avoid interference with subsistence whaling and other studies.
8. To analyze the data to test hypotheses concerning the effects of the drilling platform sounds mentioned in (3) on (a) the movement patterns and (b) the behavior of bowheads and white whales visible along their spring migration corridor in the western Beaufort Sea.

Approach and Procedures

No oil production facilities have yet been constructed in or near the spring lead systems, so no recording of underwater sounds from such an operation exists. It was decided that sounds from one of the bottom-founded caissons used for exploratory drilling in the Beaufort Sea would be the most appropriate sounds to use. No recording of sounds from such a caisson operating in winter or spring ice conditions existed during the 1989 field program. Instead, as part of this project, sounds from drilling on a grounded ice platform were recorded near Prudhoe Bay in late March 1989. These sounds were used for all playback experiments in the spring of 1989. Because the 1989 sample size was inadequate, and for other reasons, it was decided to use the same drilling sounds for playbacks in 1990.

The study had to be conducted in such a manner that it did not interfere, and was not perceived to interfere, with either subsistence whaling or the spring bowhead census. Barrow is the northeasternmost community where there is spring whaling, and the census is also done just north of Barrow. After consultation with the Barrow Whaling Captains' Association, the Alaska Eskimo Whaling Commission, and the North Slope Borough's Dept of Wildlife Management, it was agreed in early 1989 that the most suitable location for playback experiments was about 60 km NE or ENE of Pt. Barrow. In 1990, it was agreed that the work could be done as close as 15 n.mi. (28 km) beyond the northeasternmost whaling camp.

The field crew consisted of two teams. *(1)* A helicopter-supported crew deployed a U.S. Navy J-11 underwater sound projector from ice pans, and used it to project recorded drilling platform sound into leads. When whales came within visible range of the projector site, the ice-based crew documented whale movements and behavior, using a surveyor's theodolite to measure the successive bearings and distances of whales from the projector. In addition, this crew measured the rate of attenuation of underwater noise with increasing distance from the source (in this case the projector). *(2)* A second crew, in a Twin Otter aircraft, located whales and suitable projector sites, documented the behavior of whales as they swam toward and past the projector, and (in 1989) obtained known-scale vertical photos of bowheads in order to identify individuals and measure their sizes. The aircraft crew also used naval sonobuoys to monitor underwater sounds near whales exposed to projected drilling sounds.

Whale observations obtained by the two crews were complementary. Ice-based observers obtained more detailed data on the paths and speeds of some whales that passed within 1-2 km of the projector, and observed whales even when there were low clouds. The aerial observers could observe whales at any distance from the projector site, and could follow them for longer distances. Aerial observers also had a much better vantagepoint for viewing the details of behavior. However, aerial observations were only useful when the cloud ceiling was at least 460 m (1500 ft) above sea level, since bowheads sometimes react to a circling observation aircraft if it flies lower than that altitude. Low cloud frequently interfered with behavioral observations in 1989, but did so less commonly in 1990.

The ice-based crew worked from the ice on 16 days between 27 April and 26 May 1990, and on 18 days between 29 April and 30 May 1989. They conducted transmission loss tests on four days in 1990 and five days in 1989. They projected *Karluk* drilling platform sounds into the water for several hours on each of 8 days in 1990 and 11 days in 1989. On 6 days in 1990 and 5 days in 1989, bowheads were observed in waters that were ensonified by the projected drilling platform sounds. The total number of bowheads seen near the operating projector was much greater in 1990. Control data on bowheads near the quiet projector were obtained on the same six dates in 1990 plus two additional non-playback days in 1990. White whales were seen near the operating projector on one day in 1990 and four days in 1989.

The aircraft-based crew conducted reconnaissance surveys on 23 days in 1990, from 29 April to 26 May; and on 24 days in 1989, from 1 to 30 May. The aerial crew conducted 29 behavior observation sessions on 12 days in 1990, and 17 sessions on 10 days in 1989. Behavioral observations totaled 46.8 h in 1990 and 25.6 h in 1989. Of these 72.4 h of observations over the two years, 43.9 h involved presumably undisturbed bowheads (control data) and 28.5 h involved potentially disturbed bowheads.

This report concerns primarily the 1990 results. A previous report presented the detailed results from 1989 (Richardson et al. 1990a, OCS Study MMS 90-0017, NTIS PB91-105486). However, the 1989 and 1990 data on bowhead behavior and reactions to noise playbacks are integrated in this report.

Physical Acoustics

Ambient Noise

Broadband levels of ambient noise usually were within the range expected for sea state zero (flat calm) to sea state four (moderate sea) spectra. The primary contributors to the ambient noise were animal calls, ice deformation noises, and small waves. High wind-driven seas could not develop with sea ice coverage exceeding 80-90%, and work in the Beaufort was rarely attempted when wind speed exceeded 20 knots (37 km/h). Ambient noise levels in the 20-1000 Hz band averaged slightly higher in 1990 (91 dB re 1 µPa) than in 1989 (85 dB). The increased amount of open water in 1990 may have been at least partly responsible.

The median ambient noise level on a 1/3-octave basis was 76-79 dB re 1 µPa for every 1/3-octave band from 12.5 through 1250 Hz, a two decade range. In contrast, third-octave levels usually tend to decline slowly with increasing frequency. Bearded seal calls were an important contributor to the ambient noise at levels from a few hundred to a few thousand Hertz. Although the median 1/3-octave levels were relatively flat across frequency, the 5th and 95th percentiles generally declined with increasing frequency.

Ambient noise levels within ¼-s intervals were very variable. When such measurements were made over various 8½-s and 1-min periods, it was found that the median of the ¼-s measurements tended to be less than the overall average for the corresponding 8½-s or 1-min period. The largest differences between median ¼-s values and the longer-term averages tended to occur on occasions with high ambient noise. These results indicate that marine mammals may be able to hear weaker sound signals than might be expected based on conventional ambient noise data averaged over several seconds or longer--especially on days with high average levels of ambient noise. Mammals may be able to hear weak signals during the instants when ambient noise is lower than average.

Transmission Loss Tests

Transmission loss (TL) tests were conducted on 1, 2, 24, and 25 May 1990. During each test, pure tones, sweeps, and a sample of *Karluk* drilling sounds were projected into the water at a base camp on the ice, and received levels were determined at distances ranging from 100 m to ~13 km.

In general, TL data derived from the three types of signals were similar; TL increased with range in the general manner expected. However, there were a few seemingly anomalous points, in most cases for tones. This was to be expected, given that received levels of tones are especially subject to constructive and destructive interference effects associated with multipath propagation.

Simple propagation models have been fitted to the 1990 TL data. Each of these models includes a logarithmic spreading loss term and a linear term accounting for absorption and scattering losses. Spreading loss at distances exceeding 100 m from the projector was found to range from 10 log (R) to 20 log (R), depending on the water depth. The linear loss terms accounted for an additional 2-4 dB/km in most cases. The linear loss coefficients found in this study were higher than those found during previous summer and autumn studies elsewhere in the Beaufort Sea during the open water season. The additional loss during this spring study was at least partly attributable to the effects of the rough underice surface. The results of the transmission loss tests were important in deriving equations to estimate the levels received by whales during the playback experiments.

Results from 1990 were comparable to those from 1989. Preliminary indications are that the bottom influence on sound transmission is about the same throughout the study area. The acoustic propagation behavior of the study area in late April and May appears to be comparable to that of the Chukchi Sea in winter.

Playback Tests

Useful disturbance tests were conducted on six days in 1990. Sounds recorded 130 m from the actual *Karluk* drillrig were used as the stimulus during all disturbance test playbacks in 1990 as well as 1989. A model J-11 underwater sound projector suspended at depth 18 m was used in every 1990 test.

For the overall 20-1000 Hz band, the average source level in 1990 was 166 dB re 1 μPa-m. The highest source level noted during a playback was 169 dB and the lowest was 163 dB. In 1989, the average source level in the 20-1000 Hz band was 165 dB. The source level of the actual *Karluk* drillrig is unknown but higher. However, propagation loss near the actual rig in very shallow water was more rapid than that in the deeper water around playback sites. As a result, during the 1990 playbacks, the 20-1000 Hz levels received <100 m (330 ft) from the projector were somewhat lower than those at corresponding distances from the actual rig. Levels 100-200 m from the projector and the actual rig were similar. Levels >200 m from the projector exceeded those at corresponding distances from the *Karluk* rig.

The J-11 projector was effective in broadcasting components of the drilling sound above 80 Hz. The projected sounds at frequencies below 80 Hz, and especially below 63 Hz, underrepresented the corresponding components of the actual *Karluk* drillrig sounds. Below 50 Hz there was little output, even though the original *Karluk* sounds contained significant energy down at least as low as 10 Hz. The inability of any practical projector to reproduce the lowest-frequency components of industrial sound is a concern, as discussed on pages 261-263. However, at distances of a few hundred meters from the projector, where some of the most interesting biological results were obtained, overall levels in the 20-1000 Hz band were similar to those at corresponding distances from the actual rig.

Levels and spectral characteristics of the projected drilling sounds as received at various distances from the projector during playback tests are given at several places in the report, as necessary to interpret the movements and behavior of whales during playback tests. The projected *Karluk* sounds were very prominent when received about 1 km from the projector. The projected sounds diminished with increasing distance, and dropped below the background noise level in the corresponding frequency band at distances ranging from about 2 to 10 km, varying from day to day.

Infrasounds

As an indirect way to assess whether bowhead hearing capabilities may extend into the infrasonic (<20 Hz) range, where the sound projector is ineffective, a preliminary analysis was done to determine whether bowhead calls include any infrasonic components. A total of 45 bowhead calls were analyzed in waterfall format spanning frequencies from 5 to 250 Hz. These calls had been recorded with equipment effective to frequencies below 5 Hz. Few calls had any energy at frequencies as low as 50 Hz, and very few--if any--had energy below 30 Hz. One of the 45 calls was accompanied by weak components at 15-32 Hz, but it is not certain that these were part of the call. This preliminary work showed that few if any of the known types of calls include components at infrasonic frequencies. This analysis did not address the possibility that bowheads might sometimes emit calls that are confined to frequencies below 20 Hz, without any accompanying higher-frequency components.

Ambient noise levels at infrasonic frequencies are of interest with respect to questions about how far away any infrasonic components from industrial noise sources might be detectable. The ambient noise analyses mentioned above extended down to 10 Hz. Ambient noise levels at 10-20 Hz were higher than those at most higher frequencies on both a spectrum level and a 1/3-octave basis. This would tend to reduce the maximum detection radius of any man-made sounds at very low frequencies.

Bowhead Whales

Movements and General Behavior

Bowheads migrated northeast and east through the study area throughout late April and May of 1989 and 1990. In 1989, the migration was often through heavy pack ice conditions. In 1990, the ice was less compacted. Even when a broad nearshore lead extended east along the landfast ice edge through the study area, the migration corridor 35+ km ENE of Pt. Barrow was mainly along the offshore side of the lead or through the pack ice north of the lead.

Bowheads visible under undisturbed conditions in May 1989, mainly amidst the pack ice, were engaged in traveling (migration), socializing, and resting. Resting bowheads were often in small areas of open water amidst heavy ice. In 1989, many bowheads apparently migrated through the study area unseen during periods of heavy ice cover and poor weather. In May 1990, when heavy ice cover was much less common, a higher proportion of the whales observed were actively migrating northeast or east. Socializing was seen occasionally, but resting was not. No surface feeding was seen, and apparent water-column feeding was rare. A number of whales were seen surfacing with mud streaming from their bodies and (rarely) from their mouths. Several behaviors that have been observed commonly in late summer and autumn were seen only infrequently in May 1989-90: pre-dive flexes, fluke-out dives, and aerial activities. A few bouts of sexual activity were observed.

Bowhead calves and their mothers were seen only in the latter half of May in 1989 and 1990. They constituted the majority of the bowheads present in the last week of May in both years. They did not migrate as strongly or consistently eastward as did other bowheads, especially in 1989 when ice conditions were heavier. In 1989, a few mother/calf pairs traveled *west* for at least a few kilometers. One mother/calf pair identified in 1989 traveled only 12 km in 44 h. Some of these pairs may have been waiting for ice conditions to ameliorate before continuing east. During travel, bowhead calves often "rode" on the backs of their mothers during 1989, but did so less often in 1990. Riding has not been seen in late summer or autumn, when the calves are older and larger.

Drilling Noise Playbacks

Because of heavy ice conditions and poor weather during much of the 1989 field season, there were only five days in 1989 when we were able to observe bowheads exposed to projected drilling noise. All data had to be collected from holes and leads amidst the pack ice rather than along the landfast ice edge. The number of bowheads seen near the sound projector in 1989 was small, but some noteworthy data were obtained.

In 1990, weather and ice conditions were much more favorable. Bowheads were observed passing the operating sound projector on six days; control data on bowheads passing the ice camp were obtained on those six days and two additional days. Numbers of bowheads passing the ice camp tended to be higher in 1990, and several times as many data on whales near the ice camp were obtained in 1990 than in 1989. Also, considerably more control data on bowheads away from any ice camp were obtained in 1990 than in 1989.

The largest quantity of data came from 13 May 1990 when, throughout the day, a stream of bowheads migrated along a long, narrow lead through otherwise-heavy pack ice. The sound projector had been set up alongside this lead at a point where it was ~200 m (655 ft) wide. Bowheads continued to pass the projector while normal *Karluk* drilling sounds were projected. One whale came within 110 m (360 ft) of the projector. Many came within 160-195 m (525-640 ft), where the received broadband (20-1000 Hz) sound levels were about 135 dB re 1 µPa. That level was about 46 dB above the background ambient level in the 20-1000 Hz band on 13 May (Figure A). However, bowhead movement patterns were strongly affected when they approached the operating projector. When bowheads were still several hundred meters away, most began to move to the far side of the lead from the projector. (This did not happen during control periods while the projector was silent.) One approaching whale temporarily reversed course when about 400 m away before resuming eastward migration past the operating projector.

The behavior of the bowheads that came within 1 km (0.62 mile) of the operating projector on 13 May was affected in several ways, and there were less consistent behavioral effects at greater distances. Univariate and multivariate analyses showed that behavior of whales 0-½ km and ½-1 km from the projector differed significantly from behavior far away. Turns became more frequent, and there were changes in surfacing and respiration cycles. These behavioral changes were similar to the types of changes noted during previous bowhead disturbance studies. The increased frequency of turns noted within 1 km was also evident at 1-2 km, and there was evidence of subtle changes in surfacing and respiration cycles at distances as great as 2-4 km (1¼-2½ miles). Sound levels at those distances are shown in Figure A.

The results from 13 May showed that migrating bowheads would tolerate exposure to high levels of continuous drilling noise in order to continue their migration. However, the data also showed that the local movement patterns and various aspects of the behavior of these whales were affected by the noise exposure.[1]

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[1] On 13 May 1990, in addition to the playback test with normal *Karluk* drilling sounds, we also projected distorted sounds during one period while a projector was failing. The distorted sounds were less intense than the normal *Karluk* playbacks, but they were more variable and different in frequency composition. During the distorted playback, bowheads began to exhibit increased turning when they came within about 3 km (1.86 miles) of the projector. They seemed to be seeking an alternate route under the ice. In the absence of such a route, they continued toward the projector and--in at least some cases--passed within 200 m (655 ft) of it.

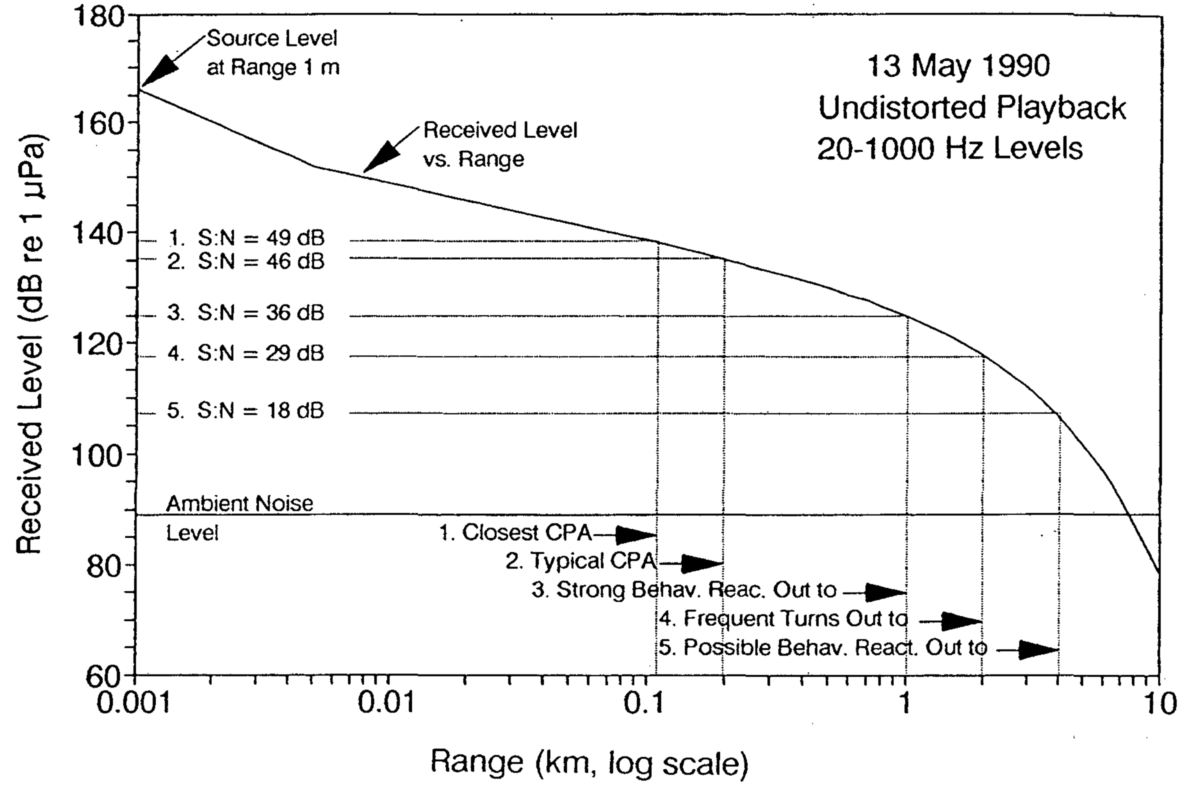

FIGURE A. Summary of major results from the 13 May 1990 playback experiment, showing received levels of *Karluk* drilling sound vs. distance from the projector, the reaction distances of bowheads, and the sound levels and signal-to-noise ratios (i.e. *Karluk* noise : ambient noise ratios) at those distances. CPA = Closest Point of Approach.

Data from other days in 1989-90 also showed that bowheads would move into the area ensonified by the sound projector, often approaching within 1 km (0.62 miles) and occasionally coming within 200 m (655 ft). The closest sighting was of a bowhead that swam to within 35 m (115 ft) of the operating projector on 10 May 1990. There was, however, evidence that some migrating bowheads diverted their courses enough to remain a few hundred meters to the side of the projector on days other than 13 May. Typically, bowheads whose initial courses would have brought them within about 500 m of the projector often diverted so as to remain >500 m to the side. Also, the frequency of turns during surfacings increased when bowheads were within 2 km (1¼ miles) of the operating projector on days other than 13 May as well as on 13 May. There was little evidence of changes in other aspects of behavior on days other than 13 May 1990.

The more conspicuous changes in movements and behavior on 13 May 1990 than on other days were presumably related to three facts: (1) On 13 May, the only available lead brought the whales within 200 m of the projector, where they were exposed to especially high sound levels. (2) The lead that channeled the whale movements on 13 May was very long, narrow and straight, making any changes in heading or behavior especially conspicuous. (3) The sample size was larger on 13 May than on any other day, making it easier to recognize effects.

There was no evidence that bowhead migration was blocked by the projected drilling sounds, and no evidence that bowheads avoided the projector by distances exceeding 1 km. We began to follow some bowheads when they were as much as 5 km (3 miles) from the operating projector, but we did not see diversion of migration paths until the whales were within a few hundred meters.

The 1989-90 data allow us to evaluate a modified and more specific version of the null hypothesis dealing with bowhead distribution and movements in relation to playbacks of platform noise. The modified null hypothesis, amended to take account of the specific characteristics of the data, is as follows (amendments are ***highlighted***):

> "Playbacks of recorded ***continuous*** noise from a bottom-founded platform ***like the Karluk drilling operation on a grounded ice pad*** will not significantly alter the migration routes or spatial distribution of bowhead whales ***visible*** in open water ***amidst the pack ice and in the seaward side of the nearshore lead system*** during spring migration ***east of*** Pt. Barrow, Alaska."

From a statistical viewpoint, this null hypothesis must be rejected. There were ***statistically significant small-scale (<1 km) alterations*** in migration routes and spatial distribution. There were also statistically significant alterations in some aspects of behavior that are related to distribution and movements (headings, turns, speed of movement). However, the demonstrated effects were localized and temporary. We conclude that the available data are consistent with this modified null hypothesis, insofar as ***biologically significant*** alterations in migration routes or spatial distribution are concerned.

The 1989-90 data on behavior allow an evaluation of a similarly-amended version of the second null hypothesis, concerning playback effects on subtle aspects of individual behavior. The 1989-90 data show that--***from a statistical viewpoint***--this null hypothesis must also be rejected. There were statistically significant changes in many aspects of individual behavior among bowhead whales approaching within 1 km of the sound projector, and a few behavioral variables were apparently affected out to 2-4 km. The ***biological significance*** of these changes in behavior is less obvious. Most aspects of behavior that were affected near the projector were affected for only about ½-1 hour.

Table A summarizes the distances from the projector at which bowheads reacted, along with the received sound levels and signal-to-noise (S:N) ratios at those distances. In this context, the S:N ratio is the difference, in decibels, between the received level of *Karluk* noise and the level of the natural ambient noise in the corresponding band.

We emphasize that all values in Table A refer to playbacks of one particular type of continuous, low-frequency sound. It should not be assumed that the same values would apply to other types of sounds.

One of the main limitations of this study is the inability of a practical sound projector to reproduce the low-frequency components of recorded industrial sounds. The *Karluk* rig emitted strong sounds down to ~10 Hz, and quite likely at even lower frequencies. It is not known whether the underrepresentation of components below 80 Hz and especially below 63 Hz during playbacks had significant effects on the responses by bowheads. Bowheads presumably can hear sounds extending well below 80 Hz, but it is not known whether their hearing extends into the infrasonic range below 20 Hz.

Table A. Reaction thresholds for bowheads exposed to playbacks of *Karluk* drilling sounds, 1989-90. The 13 May 1990 values refer to whales migrating along a narrow, constraining lead through heavy ice. The "Other" values refer to other days in 1989-90 when the ice was not as constraining.

		Closest CPA *	Typical CPA	Strong Behav. Reaction Out to	Frequent Turns Out to	Possible Behav. Reaction Out to
A. Distance						
	13 May	110 m	200 m	1 km	2 km	4 km
	Other	35 m	400 m	-	2 km	-
B. Received Level						
20-1000 Hz	13 May	138 dB*	135 dB	125 dB	118 dB	107 dB
	Other	138 *	120	-	106	106
Dominant	13 May	134 *	131	120	113	102
1/3 Octave	Other	133 *	115	-	100	100
C. Signal-to-Noise Ratio						
20-1000 Hz	13 May	49 *	46	36	29	18
	Other	44 *	26	-	12	12
Dominant 1/3	13 May	53 *	50	39	32	21
1/3 Octave	Other	49 *	32	-	17	17

* CPA = Closest point of approach. Decibel values in this column may be overestimated by as much as a few decibels, as explained in footnote 21 on page 250.

The projector adequately reproduced the overall 20-1000 Hz level at distances beyond 100 m even though components below 80 Hz were underrepresented (see p. xiv). If bowheads are no more responsive to sound components at 20-80 Hz than to those above 80 Hz, then the playbacks provided a reasonable test of bowhead responsiveness to components of *Karluk* sound above 20 Hz. No specific test of the responsiveness of bowheads to the components below 20 Hz is possible in the absence of a sound projector capable of reproducing infrasonic components. Also, this study was not designed to test the potential reactions of whales to non-acoustic stimuli detected via sight, olfaction, etc. However, in summer the responses of bowheads to actual dredges and drillships seem generally consistent with the reactions to playbacks of recorded sounds from those same sites (Richardson et al. 1990b, *Mar. Environ. Res.* 29:135-160). This observation gives us some reason for optimism that the playback method provides meaningful results.

Aircraft Disturbance

Limited observations were obtained in 1989 and 1990 on bowhead reactions to a Bell 212 helicopter. The sample size was small and most observations were unsystematic. However, one controlled overflight experiment was conducted in 1990.

Overall, the limited 1989-90 observations suggest that spring-migrating bowheads sometimes dive in response to a close approach by a turbine-powered helicopter. However, other bowheads show no obvious reaction to single passes--even at altitudes of 150 m (500 ft) or below.

There is, to date, no evidence that single helicopter overflights at altitudes of 150 m (or below) disrupt the distribution or movements of spring-migrating bowheads in any biologically significant way. However, the 1989-90 data are limited, and additional data are expected to be forthcoming from subsequent years of this project. Therefore, a final evaluation of the null hypotheses concerning effects of helicopter overflights on the distribution, movements, and behavior of bowheads is deferred until later in the project.

White Whales

Movements and General Behavior

Sightings of white whales were much more numerous than those of bowheads in May 1989. As previous workers have reported, white whales tended to be more widely scattered and slightly farther offshore than bowheads, but their migration corridors overlapped broadly. Most of the white whales seen were amidst the pack ice, although in late May a few were traveling east on the offshore side of the lead bordering the landfast ice edge.

In late April and May of 1990, white whales were seen much less regularly than in 1989. They were migrating consistently northeast and east through the pack ice or the north side of the main nearshore lead. In 1990, unlike 1989, we did not see white whales whose migration was blocked by heavy ice conditions. There was only one day in 1990 (21 May) when white whales passed the ice camp while a playback experiment was in progress.

Drilling Noise Playbacks

We observed migrating white whales close to the operating projector on four dates in May 1989. On three of these dates, at least a few white whales came within ~200 m (655 ft) of the operating projector, including a few within 50-75 m (165-250 ft). White whales that were migrating toward the projector appeared to travel unhesitatingly toward it until they came within a few hundred meters. Some white whales that came that close to the projector continued past it without apparent hesitation or turning. However, others did react temporarily to the noise, or perhaps to visual cues, at distances on the order of 200-400 m (655-1310 ft).

On 14 May 1989, a substantial proportion of the white whales that came within 200-400 m of the projector slowed down, milled, and in some cases reversed course temporarily. This interruption of migration was very obvious, but lasted only several minutes. Then the whales continued past the projector, in some cases passing within 50-100 m (165-330 ft) of it.

On the one day in 1990 when white whales were seen near the projector, several groups migrated past within ~400 m (1310 ft). The closest confirmed approach to the operating projector in either year was on 21 May 1990, when a group of four white whales approached to within 15 m (50 ft). However, they did not dive (and thus expose themselves to strong low frequency noise) until they were 64 m (210 ft) away. Another group seen on that day turned away when they came within 40 m (130 ft), and dove at that distance.

We saw no evidence that white whales reacted at distances greater than 200-400 m even though projected drilling noise was measurable as much as several kilometers away. We suspect that this was related to the poor hearing sensitivity of white whales at the low frequencies where the *Karluk* drilling sounds were concentrated. At distances beyond ~200 m, received levels of the low-frequency drilling sounds (on a 1/3-octave basis) usually were less than the measured hearing sensitivity of white whales.

The observed reactions may have been to weak artifactual components of the projected sound at frequencies above 2-3 kHz rather than to the stronger *Karluk* components between ~63 Hz and ~300 Hz. Although weak, the high-frequency components were potentially audible to white whales at somewhat greater ranges, given the much better hearing capabilities of white whales at higher frequencies.

Overall, some white whales reacted to the projected sounds at distances as great as 200-400 m (655-1310 ft), but other individuals approached considerably closer. The minimum confirmed distances from the operating projector were 15 m (50 ft) for white whales at the surface and 40 m (130 ft) during a dive. Estimated received sound levels several meters or more below the surface at these distances were as follows:

Range (m)	Range (ft)	Broadband (dB re 1 μPa)	Max. 1/3-Octave (dB re 1 μPa)
400	1310	112	106
200	655	118	112
40	130	134[a]	128[b]

[a] S:N≈36 dB

[b] S:N≈42 dB

The 1/3-octave levels of drilling sound noted above for the observed minimum and maximum reaction distances quite likely do not represent the actual acoustic reaction thresholds. Although maximum projected and received levels occurred in 1/3-octave bands near 200 Hz, the levels received 200-400 m from the projector in that frequency band appear to be too low to have been heard. Acoustic reactions are more likely to depend on reception of lower level sounds at higher frequencies where the white whale hearing apparatus is more sensitive.

The maximum acoustic reaction distance of white whales near a shallow-water drillsite like *Karluk* is predicted to be similar to that observed in our tests (a few hundred meters). Reaction distances near the actual drillsite might, in fact, be less than those near the projector if the observed reactions were to the weak high-frequency system noise rather than the drilling noise *per se*. This high-frequency noise would not be present near the actual drillsite.

Minimum reaction distances near an actual drillsite like *Karluk* probably exceed those observed near the projector (15-50 m) because of the higher noise levels and other stimuli present within ~200 m of the actual site relative to those at corresponding distances from the projector site.

The two hypotheses concerning reactions of white whales to playbacks of platform noise deal with (1) migration routes and spatial distribution, and (2) subtle aspects of individual behavior. The wording is the same as that for bowheads (see above). We can only draw conclusions about the effects of playbacks of ***continuous noise from drilling on a bottom-founded ice platform like Karluk***. Also, the data apply to white whales ***visible*** while migrating through ***pack ice and along the seaward side of the nearshore lead east of Pt. Barrow***.

We conclude that playbacks of sounds from drilling on a bottom-founded ice platform like *Karluk* have no biologically significant effects on migration routes and spatial distribution of white whales visible while migrating through pack ice and along the seaward side of the nearshore lead east of Point Barrow in spring. Furthermore, we expect that maximum reaction distances of white whales to an actual drillsite like *Karluk* (a few hundred meters) would be similar to those observed during the playback experiments. In drawing these conclusions, we consider that the observed temporary hesitation and minor changes in migration paths exhibited by some white whales within 200-400 m of the noise source were not biologically significant. Our acceptance of the amended null hypothesis is based on a "weight of evidence" approach; the available data are not suitable for a statistical test of the hypothesis.

We emphasize strongly that our conclusions relating to the "distribution and movements" hypothesis pertain only to continuous low-frequency drilling noise from a bottom-founded ice platform like Karluk. Reaction distances to some other sources of industrial noise may be very different. This is evident from the reactions of spring-migrating white whales in the Canadian high arctic to ships and icebreakers at very long distances (Finley et al. 1990, *Can. Bull. Fish. Aquatic Sci.* 224:97-117). To understand the effects of industrial noises related to oil production on spring-migrating white whales in the Beaufort Sea, we need to test their reactions to additional types of noise whose characteristics differ from those studied in 1989-90.

The available data are not adequate for a test, statistical or otherwise, of the second hypothesis, concerning effects of *Karluk* drilling noise on subtle aspects of the individual behavior of white whales.

Aircraft Disturbance

The 1989-90 observations of the movements and behavior of white whales in the presence of a Bell 212 helicopter or Twin Otter fixed-wing aircraft were largely anecdotal but generally consistent with previous evidence. Reactions to turbine-powered aircraft during the spring migration near Pt. Barrow are variable. Some individuals show no overt response to a fixed-wing aircraft or helicopter flying at low level, or to a helicopter standing on the ice edge (with engines running) within 100-200 m (330-655 ft) of the whales. Others look upward or dive abruptly when an aircraft passes over at altitudes at least as high as 460 m (1500 ft). Some white whales whose paths come within 100 m of a helicopter on the ice with its engines running may divert as much as 100 m away from the helicopter. It is not known whether these small-scale and apparently brief reactions are to the noise from the aircraft, visual cues, or both.

The two hypotheses concerning reactions of white whales to helicopter overflights deal with effects on (1) migration routes and spatial distribution, and (2) subtle aspects of individual behavior. The wording is the same as that for bowheads (see p. xviii, above). The available spring data apply only to ***Bell 212*** helicopters, and to white whales ***visible*** while migrating through ***pack ice and along the seaward side of the nearshore lead east of Pt. Barrow.***

The limited results available from 1989-90 are consistent with the null hypothesis about helicopter effects on migration routes and spatial distribution (amended as highlighted above). The data suggest that single overflights by a helicopter of the Bell 212 class do not cause blockage or biologically significant diversion of the spring migration of white whales traveling in pack ice or along the seaward side of the nearshore lead. We consider that diversion of migration routes by 100 m or 330 ft (as may have occurred on 21 May 1990) is not biologically significant. This preliminary assessment is based on the "weight of evidence"; the available data are not amenable to a statistical test. The data are limited and non-systematic, and additional data are likely to be obtained in future years of this study. Hence, a final determination as to the validity of the "distribution and movement" null hypothesis for white whales is postponed until later in the project.

The available data are not adequate for a test, statistical or otherwise, of the hypothesis concerning helicopter effects on subtle aspects of the individual behavior of white whales. It is obvious that short-term effects on their behavior do occasionally occur (hasty dives, looking at the passing helicopter). However, the available data do not allow quantification or assessment of biological significance.

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Dr. Thomas Albert	North Slope Borough Dept of Wildlife Management,
Mr. Mark Fraker	BP Exploration (Alaska), Inc.,
Dr. Roger Green	University of Western Ontario,
Mr. Allen Milne	Sci. Rev. Board Chairman,
Mr. Ron Morris	Nat. Mar. Fish. Serv.,
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GLOSSARY

absorption. The process by which sound energy is converted into heat.

acoustic power. The energy per unit time, measured in watts. The acoustic power is proportional to acoustic pressure squared.

acoustic pressure. Pressure variations around an ambient static pressure (such as the hydrostatic pressure in water at some depth) at acoustic frequencies. These are very small pressures compared to the static pressure or compared to shock or blast wave pressures.

ambient noise. Background noise; noise not of direct interest during a measurement or observation. Excludes sounds produced by the measurement equipment, such as cable flutter.

ASL. Above sea level.

audiogram. A graphical depiction of auditory thresholds, showing the sound levels that are barely detectable by an animal, in the absence of significant background noise, as a function frequency.

auditory sensitivity. An animal's hearing sensitivity as a function of frequency.

auditory threshold. The minimum amplitude of sound that can be perceived by an animal in the absence of significant background noise. Auditory threshold varies with frequency and is inversely related to the animal's auditory sensitivity.

bandpass filter. A filter with high-pass and low-pass cutoff frequencies, designed to pass only a desired band of frequencies.

bandwidth. A range of frequencies.

blow interval. The interval, in seconds, between two successive respirations within the same surfacing by a whale.

CPA. Closest Point of Approach.

critical band. The frequency band within which background noise can affect detection of a sound signal at a particular frequency.

critical ratio. The ratio of power in a barely-audible tone to the spectrum level of background noise at nearby frequencies.

continuous wave. A sound whose waveform continues with time.

cylindrical spreading. Sound spreading as cylindrical waves. The transmission loss for cylindrical spreading is given by $10*\log_{10}(\mathrm{Range}/R_0)$, where R_0 is some reference range. The received level diminishes by 3 dB when range doubles, and by 10 dB for a tenfold increase in range.

cylindrical wave. A sound wave whose fronts are cylindrically shaped. For a point source in shallow water, a cylindrical wave forms at distances large compared to the water depth because of the way reflected sound from the surface and bottom reinforces the direct wave.

decibel (dB). A logarithmically based relative measure of sound strength. A sound pressure P can be expressed in dB as a sound pressure level of $20*\log_{10}(P/P_{ref})$, where P_{ref} is a reference pressure (usually a standard pressure like 1 microPascal). Note that $20*\log(X)$ is the same as $10*\log(X^2)$, where X^2 is the mean square sound pressure and is proportional to power, intensity or energy.

DIFAR. A type of sonobuoy (AN/SSQ-53B) that has the ability to determine the direction of arrival of a sound.

electrical noise. Noise generated by electronic circuits, as distinct from acoustic noise.

filter. An instrument or mechanism for restricting or altering the frequency range or spectral shape of a waveform.

fluke-out dive. A dive in which the whale raises its tail flukes above the surface of the water as it dives.

frequency. The rate at which a repetitive event occurs, measured in hertz (cycles per second).

hertz (Hz). A measure of frequency corresponding to a cycle per second.

high-pass filter. A filter passing sounds above a specified frequency.

hydrophone. A transducer for detecting underwater sound pressures; an underwater microphone.

infrasound. Sound energy at frequencies too low to be directly audible to humans; generally taken to be sound at frequencies below 20 Hz.

J-11. A particular type of U.S. Navy underwater sound projector.

***Karluk*.** *Karluk* was a grounded ice platform that was constructed in 6 m of water near Prudhoe Bay, Alaska, during the winter of 1988-89. The *Karluk* ice platform was used as a drillsite during that winter. The underwater sounds projected during playback experiments in this study were recorded 130 m from *Karluk* while it was drilling during March 1989.

level. The term "level" is usually applied to sound amplitudes, powers, energies or intensities expressed in dB.

Lloyd mirror effect. The diminished pressure of a sound from an underwater source when it is received near the water/air boundary (the surface). The reflected sound wave is inverted (out of phase) with respect to the incident sound wave, and their sum at the receiver approaches zero as the receiver approaches the surface.

low-pass filter. A filter passing sounds below a specified frequency.

masking. The obscuring of sounds of interest by stronger interfering sounds.

microbar (μbar). A unit of pressure previously used as a reference pressure in dB level measurements. A μbar is equivalent to 1 dyne/cm^2 and to 0.1 pascal, or 10^5 μPa.

noise. Sounds that are not of particular interest during an acoustic study and that form the background to the sound being studied. Noise can include both natural sounds and man-made sounds.

micropascal (μPa). The usual reference pressure in underwater sound level measurements.

octave band. A frequency band whose upper limit in hertz is twice the lower limit.

one-third octave band. A frequency band whose upper limit in hertz is $2^{1/3}$ times the lower limit. Three one-third octave bands span an octave band. Such bands have widths proportional to the center frequency; the center frequency is given by the square root of the product of the upper and lower limit frequencies, and the bandwidth is 23% of the center frequency. There is a standard set of one-third octave frequency bands for sound measurements.

pascal. A unit of pressure equal to 1 newton per square meter.

peak level. The sound level (in dB) associated with the maximum amplitude of a sound.

point source. A hypothetical point from which sound is radiated. The concept is useful in describing source levels by a pressure level at unit distance. The concept is an abstraction; to describe a 300 m ship as a point source stretches the imagination, but at a distance of 10 n.mi. the received sound may as well have come from a point source radiator.

power density spectrum. The result of a frequency spectrum analysis to determine the distribution of power in a signal vs. frequency where continuously distributed sound (not tones) is the important component of the signal. Correct units of a power density spectrum are watts/Hz but the usual units in acoustics are μPa^2/Hz, because the power is proportional to the mean square pressure and pressure is the commonly measured physical quantity.

power spectrum. The result of a frequency spectrum analysis to determine the distribution of power in a signal vs. frequency where tones are the important components of the signal. Correct units of a power spectrum are watts but the usual units in acoustics are μPa^2, because the power is proportional to pressure squared and pressure is the commonly measured physical quantity.

pre-dive flex. A distinctive concave bending of the back occasionally exhibited by bowheads while they are at the surface but shortly before they are about to dive.

pressure. A physical manifestation of sound. The dimensions of pressure are force per unit area. The commonly used unit of acoustical pressure is the micropascal.

propagation loss. The loss of sound power with increasing distance from the source. Identical to transmission loss. It is usually expressed in dB referenced to a unit distance like 1 m. Propagation loss includes spreading, absorption and scattering losses.

proportional bandwidth filters. A set of filters whose bandwidths are proportional to the filter center frequencies. One octave and one-third octave filters are examples of proportional bandwidth filters.

pure tone. A sinusoidal waveform, sometimes simply called a tone. There are no harmonic components associated with a pure tone.

reflection. The physical process by which a traveling wave is returned from a boundary. The angle of reflection equals the angle of incidence.

refraction. The physical process by which a sound wave passing through a boundary between two media is bent. If the second medium has a higher sound speed than the first, then the sound rays are bent away from the perpendicular to the boundary; if the second medium has a lower sound speed than the first, then the sound rays are bent toward the perpendicular. Snell's law governs refraction: $c_2*\sin\theta_1 = c_1*\sin\theta_2$, where c is the sound speed, subscript 1 refers to the first medium and subscript 2 refers to the second medium, and the angles are measured from the perpendicular to the boundary. Refraction may also occur when the physical properties of a single medium change along the propagation path.

RL. Received Level; the level of sound reaching a location some distance from the sound source (*cf.* source level).

scattering. The physical process by which sound energy is diverted from following a regular path as a consequence of inhomogeneities in the medium (volume scattering) or roughness at a boundary (boundary scattering).

signal. A sound of interest during an acoustic study.

S:N. Signal-to-Noise ratio; the difference in level, measured in decibels, between a signal of interest (in this study, usually *Karluk* sound) and the background noise at the same location (in this study, usually ambient noise).

sonobuoy. A sound monitoring and transmitting device that includes a hydrophone, amplifier and an FM radio transmitter. Sonobuoys are designed to be dropped into the water from an aircraft. They can also be deployed from the surface. Sounds in the water can be monitored from a remote location via radio receivers.

sound. A form of energy manifested by small pressure and/or particle velocity variations.

sound pressure. The pressure associated with a sound wave.

sound pressure density spectrum. The description of the frequency distribution of sound pressure in which the actual pressure at any frequency is infinitesimal but, integration over any non-zero frequency band results in a non-zero quantity. The correct dimensions of sound pressure density spectrum are pressure squared per unit frequency; a common unit is $\mu Pa^2/Hz$. *cf.* power density spectrum.

sound pressure density spectrum level. The measure in decibels of sound pressure density spectrum. A common unit is dB re 1 $\mu Pa^2/Hz$.

sound pressure level (SPL). The measure in decibels of sound pressure. The common unit is dB re 1 µPa.

sound pressure spectrum. The description of the frequency distribution of a sound pressure waveform consisting of tones. The dimension is that of pressure; a common unit is the micropascal.

source level. A description of the strength of an acoustic source in terms of the acoustic pressure expected a hypothetical reference distance away from the source, typically 1 m, assuming that the source is a point source. Source level may be given in units of dB re 1 µPa-m. Source level may vary with frequency (see source spectrum level) but it may be given for some band of frequencies.

source spectrum level. A description in decibels of the strength of an acoustic source as a function of frequency. The description is meaningful for sources of tones. Source spectrum levels are described in decibels referred to a unit pressure at a unit distance, such as dB re 1 µPa-m.

spectrum level. See "sound pressure density spectrum level".

spherical spreading. Sound spreading as spherical waves. The transmission loss for spherical spreading is given by $20*\log_{10}(\text{Range}/R_0)$, where R_0 is some reference range. The received level diminishes by 6 dB when range doubles, and by 20 dB for a tenfold increase in range.

spherical wave. A sound wave whose fronts are spherically shaped. Such a wave forms in free space without reflecting boundaries or refraction. Typically, spherical waves are emitted by point sources and retain their sphericity until the influence of reflected waves or refraction becomes noticeable.

spreading loss. The loss of acoustic pressure with increasing distance from the source due to the spreading wavefronts. There would be no spreading loss with plane waves. Spreading loss is distinct from absorption and scattering losses.

SSDC. Single Steel Drilling Caisson or Steel-Sided Drilling Caisson; this is a mobile bottom-founded drilling platform constructed from part of a supertanker.

surfacing. As defined in this study, a surfacing by a whale is the interval from the arrival of the whale at the surfacing following one long dive until the start of the next long dive. Periods while the animal is just below the surface between breaths (blow intervals) are not counted as dives. Equivalent to the term "surfacing sequence" used by some authors.

threshold of audibility. The level at which a sound is just detectable. The threshold of audibility depends on the listener and varies with frequency.

third octave. Abbreviation for one-third octave (see above).

time delay. A time difference between related events, such as the time between arrivals of a sound wave at two receivers, or the time between sound transmission and the reception of its reflection.

tone. A sinusoidal waveform, sometimes called a pure tone. There are no harmonics. A tone is distinct from waveforms consisting of components continuously distributed with frequency.

transducer. A device for changing energy in one form (say mechanical) into energy in another form (say electrical). An acoustic transducer might change a pressure waveform into an electrical waveform, or vice versa. Microphones, hydrophones, and loudspeakers are examples of transducers.

transmission loss. The loss of sound power with increasing distance from the source. Identical to propagation loss. It is usually expressed in dB referenced to a unit distance like 1 m. Transmission loss is includes spreading, absorption and scattering losses.

waterfall spectrogram. A graphical depiction of the intensity of sound components at various frequencies over time. Time and frequency are shown on the X and Y axes, and intensity is shown as a third dimension. A waterfall graph usually indicates only relative power.

waveform. The functional form, or shape, of a signal or noise vs. time.

wavelength. The length of a single cycle of a periodic waveform. The wavelength λ, frequency f and speed of sound c are related by the expression $c = f*\lambda$.

INTRODUCTION

The possible effects of underwater noise from offshore oil and gas activities have been a significant concern to Minerals Management Services (MMS), the National Marine Fisheries Service (NMFS), and other agencies for several years. Hence, MMS has funded studies to document the characteristics of oil industry noises and their effects on the behavior of bowhead and gray whales (e.g. Gales 1982; Malme et al. 1984; Richardson et al. 1985b; Miles et al. 1987; Ljungblad et al. 1988). The oil industry has funded related studies of the reactions of bowhead whales to oil industry operations in the Alaskan Beaufort Sea (e.g. LGL and Greeneridge 1987). These and other similar studies have been reviewed and summarized recently (Richardson et al. 1991; Richardson and Malme in press).

Prior to this study, all systematic studies of disturbance to bowheads had been done in summer or early autumn when the whales are either in open water or in loose pack ice where their movements are relatively unrestrained by ice. There had been no work on the disturbance reactions of bowheads migrating in leads through areas of heavy ice cover--the normal situation in spring. Also, there had been no systematic scientific study of the suggestion by Inupiat whalers that bowhead whales are especially sensitive to noise in the spring.

The sounds considered in the summer-autumn studies conducted in the Beaufort Sea have been those associated with some of the major offshore exploration activities, *viz* aircraft and boat traffic, marine seismic exploration, drillships, and offshore construction. Only a very limited effort has been devoted to the reactions of bowheads to icebreaking, which is a particularly noisy activity (Greene 1987a; Richardson et al. 1991). Reactions of bowheads to sounds from an oil production platform have not been studied, in part because no production platforms exist in arctic waters deeper than a few meters. Reactions of migrating gray whales to noise from a production platform were studied by Malme et al. (1984), but the type of platform involved was very different from the types likely to be used in the Arctic.

The National Marine Fisheries Service took note of the above situation in its recent Biological Opinions on lease sales in the Beaufort and Chukchi seas. NMFS believes that development and production activities in spring lead systems used by bowheads might, in certain circumstances, jeopardize the continued existence of the Western Arctic bowhead whale population (Evans 1987; Brennan 1988; Fox 1990). The possibility of significant disturbance in spring lead systems, when bowheads may have few or no optional migration routes, was one of the factors about which NMFS was concerned.

The beluga or white whale is the one other cetacean that migrates through the spring lead systems in a manner similar to the bowhead. The sensitivity of various populations of white whales to several types of human activities and underwater noises has been studied in summer in Alaska, in late spring and summer in the Mackenzie Delta area, and in spring in the eastern Canadian High Arctic. There has also been a playback study with captive white whales (Thomas et al. 1990). The sensitivity of the white whales in these situations varied widely. There was great tolerance in some situations. However, white whales exhibited strong avoidance reactions to ships and icebreakers at very great distances during spring in the eastern high arctic (LGL and Greeneridge 1986; Cosens and Dueck 1988; Finley et al. 1990). The responsiveness of white whales to underwater noise during the spring migration around western and northern Alaska has not been studied previously.

In order to answer some of these questions, MMS has funded this study. The main objectives are to determine the short-term effects of production platform noise and icebreaker noise on the movements and behavior of bowhead and white whales migrating through open leads and pack ice near Pt. Barrow, Alaska, in spring. A related objective is to determine the characteristics of sound propagation and of natural ambient noise in spring lead systems. These physical acoustic phenomena affect the received levels and prominence of man-made noise. Reactions of whales to helicopter overflights are also to be determined when possible.

This report describes results from 1990, the second year of a continuing study. The study will continue for at least one additional spring season, in 1991. In 1989, we obtained

- considerable information on physical acoustic phenomena (ambient noise and sound propagation),
- some data on reactions of bowheads and white whales to playbacks of continuous sounds from one drilling platform: a rig on a bottom-founded ice pad, and
- limited data on reactions of bowheads and white whales to aircraft.

However, weather and ice conditions in 1989 were not good, and relatively few observations of bowheads were possible. Weather and ice conditions in 1990 were much more amenable to the types of fieldwork necessary in this study. In 1990, we collected additional data on physical acoustics, limited additional data on whale reactions to helicopters, and many more data on reactions of bowheads to the same type of drilling noise used in 1989. In 1991 the top priority will be to test the reactions of bowheads to a different and more variable type of industrial noise: icebreaker sound.

The report on the first year of the study (Richardson et al. 1990a) contains much background information that is not repeated here. That report includes a summary of the distribution and movements of bowhead and white whales in spring. It also provides brief reviews of previous studies of the disturbance responses of those species, and of the possible characteristics of underwater sounds from spring production activities (pages 2-17).

Objectives and Rationale

General Objectives

In early 1988, MMS requested proposals for an experimental study of the effects of noise from oil production activities on bowhead and (secondarily) white whales during their spring migrations around Alaska. The overall objectives of the study, as defined by MMS, were

1. "To quantitatively characterize the marine acoustic environment including sound transmission loss and ambient noise within the nearshore leads of the Alaskan Chukchi Sea and Beaufort Sea in the spring.
2. "To quantitatively describe the transmission loss characteristics of underwater sound produced by production platforms and icebreakers in the spring lead study area.
3. "To quantitatively document the short term behavioral response of spring migrating bowhead and, as possible, beluga [white] whales resulting from exposure to the [above] sources (see objective 2) of production sounds.

4. "To assist and coordinate with other MMS sponsored studies and local resource users to maximize collection of needed data and avoid conflict with subsistence whaling activities.
5. "To analyze acquired and synthesized data to test the generalized null hypothesis."

Rationale for Various Study Components

The rationale for studying topics such as sound transmission loss, ambient noise levels, and received sound levels near whales requires some explanation. These data are needed in order to develop quantitative models for predicting the radii of noise detectability and noise responsiveness around the specific types of noise sources that are tested. The basic components and interrelationships of this model are illustrated in Figure 1.

The underwater noise received from an industrial source diminishes in level with increasing distance from the source. The rate of transmission loss depends on water depth, bottom conditions, ice conditions and other factors. Hence, the slope of the received level vs. range curve illustrated in the diagram can vary from place to place and time to time. The transmission loss properties of a particular study area need to be studied during the season of interest in order to make meaningful predictions of received noise levels as a function of range.

The level of the natural ambient noise has a major influence on the maximum distance to which man-made noise can be detected. Man-made noise is normally detectable by an animal (or hydrophone) if its received level exceeds the level of natural background noise at similar frequencies. The range at which the received level of man-made noise diminishes below the ambient noise level is (to a first approximation) the maximum radius of detectability (Fig. 1). Beyond that distance, the man-made noise will be weaker than the natural background noise, and is likely to be undetectable. Closer to the source of man-made noise, the received level of man-made noise will exceed the ambient noise level and the man-made noise is likely to be detectable. Ambient noise levels vary naturally from day to day as a function of wind, waves, ice conditions, calling rates by animals, and other factors. Day-to-day variations of ±10 dB or even ±20 dB are not uncommon. A 10 or 20 dB change in the ambient level has a drastic change on the range at which the received level of man-made noise falls below the ambient noise level, and thus on the radius of detectability of the man-made noise. Hence, it is important to characterize the typical ambient noise levels in the study area and season, the normal range of variation of these ambient noise levels, and the factors affecting ambient noise levels in any particular circumstance.

In most previous studies of the disturbance reactions of marine mammals, it has been found that disturbance responses do not begin until the received level of man-made noise exceeds the minimum detectable level by a substantial margin. This has proven to be the case in studies of bowhead whales, including the 1989-90 phases of this study. Thus, the received level of man-made noise diminishes below the response threshold before it diminishes below the ambient noise level and becomes inaudible (Fig. 1). In order to quantify the responsiveness of bowheads and white whales to man-made noise, it is necessary to determine the response threshold level. This will not be a constant, since whale responsiveness varies considerably. As a minimum, the average response threshold should be determined. If sample size allows, the noise levels to which various percentages of the animals react should also be

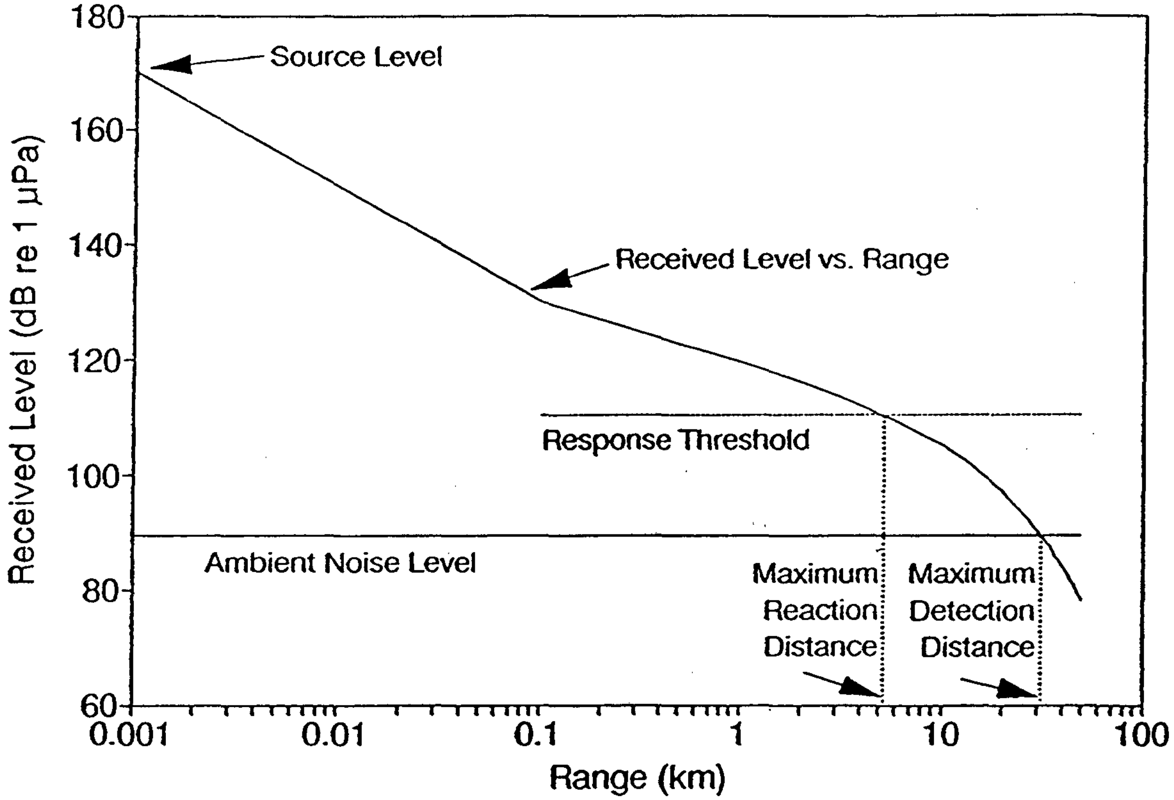

FIGURE 1. Components of a simple zone of acoustic influence model. See text for explanation.

determined. The lower the response threshold, the greater the distance at which the received level of man-made noise will diminish below that threshold.

One additional component of the zone of acoustic influence model is the source level of the man-made noise. An increase in source level will shift the received level vs. range curve upward by a corresponding amount. This shift will result in an increase in the distances at which the received level diminishes below the response threshold (= maximum reaction distance) and the ambient noise level (= maximum detection distance).

In many cases the source level of the sounds emitted during a playback experiment may be less than that of the actual industrial activity being simulated, e.g. due to projector limitations. If the source levels of the projector and the actual industrial activity are known, along with the other components of the model (Fig. 1), then it is possible to estimate the maximum reaction and detection distances around the actual industrial site based on the results collected near the projector.

Thus, by considering the source level of man-made noise, its propagation loss, the ambient noise level, and the response threshold of whales, a meaningful quantitative model of acoustic influence can be developed. This study aims to collect the types of data needed to quantify, for particular situations, the conceptual model illustrated in Figure 1 (see Fig. 95, p. 254).

Specific 1990 Objectives

The specific objectives of the 1989 and 1990 phases of this project were similar. The specific objectives for 1989 were given by Richardson et al. (1990a:17). Because of the poor weather and ice conditions in 1989, and the low numbers of whales accessible in that year, the data on reactions to drilling platform sounds acquired in 1989 were too sparse to be conclusive. Hence, the highest priority during the 1990 field program, as in 1989, was to study the reactions of bowheads to noise from a bottom-founded drilling or production platform. When possible, reactions of white whales to this sound were to be determined as well. Underwater playback techniques were to be used to simulate the noise from an actual platform. As a lower priority, the reactions of bowheads and white whales to actual helicopter overflights were to be determined if opportunities allowed. Because of concern about the effects of low-frequency industrial sound components on bowheads, and the inability of a practical sound projector to reproduce those components, several indirect methods of addressing the importance of low frequency components were identified as objectives in 1990.

The specific objectives for the second field season, in 1990, were as follows:

1. To measure ambient noise levels and characteristics in leads and cracks along the spring migration corridor of bowhead and white whales in the western Beaufort Sea, including infrasonic components.[1]
2. To measure and model transmission loss of underwater sound along that part of the spring migration corridor, based on playbacks of (a) test tones at selected frequencies

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[1] Infrasound is sound whose frequency is too low to be heard by humans. The lower limit of useful human hearing is usually taken to be 20 Hz. In this report, we consider sounds at frequencies <20 Hz to be infrasounds.

between 50 Hz and 10 kHz, and (b) continuous drilling platform sound (*Karluk* sounds).[2]

3. To measure the short-term behavioral responses of bowheads and (as possible) white whales visible in open water areas along their spring migration corridor in the western Beaufort Sea to underwater playbacks of continuous drilling platform sound (*Karluk* and CIDS sounds).[2]
4. To collect some of the data needed to assess the importance of the infrasonic components (<20 Hz) of industrial noise; specifically, to measure ambient noise at infrasonic frequencies, and determine whether bowhead calls contain infrasonic components.[1]
5. To measure the short-term behavioral responses of bowheads and (as possible) white whales visible in open water areas along their spring migration corridor in the western Beaufort Sea to actual helicopter overflights.
6. To document, as opportunities allow, other aspects of the movements, behavior, basic biology, disturbance responses and acoustic environment of bowheads and white whales along their spring migration corridor in the western Beaufort Sea.
7. To assist and coordinate with other studies and local resource users to maximize collection of needed data and to avoid interference with subsistence whaling and other studies.
8. To analyze the data to test hypotheses concerning the effects of the drilling platform sounds mentioned in (3) on (a) the movement patterns and (b) the behavior of bowheads and white whales visible along their spring migration corridor in the western Beaufort Sea.

The Null and Alternate Hypotheses

MMS initially indicated that the *primary purpose* of the study was to test the following generalized null hypothesis:

> "Noises associated with offshore oil and gas production activities *will not* significantly alter the migratory movements, spatial distribution, or other overt behavior of bowhead whales during the spring migration in the eastern Chukchi and western Beaufort Seas."

MMS indicated that the *secondary purpose* of this study was to test a similar generalized null hypothesis concerning white whales.

During the planning phase of this study, the hypotheses to be assessed were made more specific in four ways: (1) the types of oil and gas activities of concern, (2) the criteria of whale behavior to be considered, (3) the geographic location and environmental circumstances of the tests, and (4) the fact that playback techniques were to be used to simulate the noise from a platform. Four null hypotheses of a more specific nature were developed for each of the two whale species.

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[2] The original objective was to project effectively those components of *Karluk* sound above 20 Hz. This was not possible with any practical projector.

1. Playbacks of recorded noise from a bottom-founded platform will not (or alternatively will) significantly alter measures of migration routes and spatial distribution of whales in the open water of nearshore lead systems during the spring migration near Pt. Barrow, Alaska.
2. Playbacks of recorded noise from a bottom-founded platform will not (or alternatively will) significantly alter subtle aspects of individual whale behavior in the open water of nearshore lead systems during the spring migration near Pt. Barrow, Alaska.
3. Helicopter overflights will not (or alternatively will) significantly alter measures of migration routes and spatial distribution of whales in the open water of nearshore lead systems during the spring migration near Pt. Barrow, Alaska.
4. Helicopter overflights will not (or alternatively will) significantly alter subtle aspects of individual whale behavior in the open water of nearshore lead systems during the spring migration near Pt. Barrow, Alaska.

MMS indicated that greater emphasis should be placed on hypotheses (1) and (3) relating to effects on migration routes and distribution, than to hypotheses (2) and (4), relating to subtle aspects of the behavior of individual whales. However, LGL undertook to address hypotheses (2) and (4) as well, at least for bowheads. Difficulties in observing some aspects of the individual behavior of white whales from an aircraft circling at high altitude made it doubtful whether hypotheses (2) and (4) could be assessed for white whales.

Approach

This is a complex study with many interrelated tasks or components. This section provides a brief description of the overall approach. This may be helpful in understanding the relationships among the various tasks. Methods are described in more detail in a later section (METHODS).

The general concept was that reactions of bowhead and white whales to industrial noises would be tested by using an underwater sound projector to introduce recorded noise into a lead through which whales were migrating. The movements and behavior of whales would be documented as they approached and passed the sound projector. Industrial sound levels reaching the whales at various distances from the projector were to be measured with sonobuoys or hydrophones, supplemented by acoustic modeling procedures. Reactions to helicopter overflights were to be determined using an actual helicopter rather than playback techniques.

LGL is responsible for the project as a whole, and for all biological components of the work. Subcontractor Greeneridge Sciences Inc. is responsible for providing and operating acoustical equipment, and for analyzing and reporting most of the physical acoustics results. Subcontractor BBN Systems & Technologies Corp. was responsible for sound propagation modeling during 1989.

The contract was awarded to LGL in the autumn of 1988. First-year funding was provided in two stages. Initial funding covered the planning phase (October 1988 to April 1989). After it was determined that the project likely would receive the necessary approvals and permits, incremental funding was provided for the 1989 fieldwork, analysis and reporting.

1989 Planning Phase

During the planning phase, we contacted and met with representatives of three local organizations: the North Slope Borough (NSB), Alaska Eskimo Whaling Commission (AEWC), and Barrow Whaling Captains' Association (BWCA). The purposes of these communications were (1) to obtain information about local conditions that would be helpful in planning the study, and (2) to avoid any actual or perceived interference with their ongoing activities, most notably whaling and the spring bowhead census. As part of this consultation process, project personnel attended a public meeting in Barrow in January 1989 and a meeting of the BWCA in February 1989. In addition, we contacted and met with representatives of the National Marine Mammal Laboratory (NMML) aerial photogrammetry group, who were also planning to work near Barrow in the spring of 1989.

Prior to the 1989 fieldwork, the acoustic environmental conditions near Pt. Barrow during spring were reviewed, modeled and interpreted (Malme et al. 1989/1990; Richardson 1989). The main objective was to determine how far from Barrow this study would have to be conducted in order to avoid acoustic interference with whaling or the census near Barrow. In addition, Miller (1989) reviewed available literature on spring ice conditions and the spring whale migration near Barrow to assist in determining the best site for the fieldwork.

A study area was then selected based on all of the above mentioned discussions and considerations. It was decided that experimental work should be centered about 60 km northeast or east of Point Barrow. To confirm that sounds projected into the water in that region would not reach the whaling or whale census areas, two preliminary sound transmission loss tests were conducted there in late April 1989, prior to the main field season in May 1989. These tests were designed to check the acoustic predictions developed by Malme et al. (1989/1990) and Richardson (1989).

At the end of March 1989, a trip was made to Prudhoe Bay to record the sounds produced by drilling on a grounded ice platform ("*Karluk*") in 6 m of water. Production platforms similar to those that might be used in or near spring lead systems have not been constructed, and no recording of sounds from an icebound concrete or steel drilling caisson were available in early 1989. In the absence of recordings of such sounds, the under-ice noise from the *Karluk* platform was selected as having the most suitable characteristics for use during playback experiments during 1989. In order to maximize the sample size, it was decided to use this one type of industrial noise in all playback tests during 1989.

Plans for the 1989 fieldwork were reviewed and refined at a meeting of the project's Scientific Review Board (SRB) held in early April 1989. The SRB included representatives of the three concerned local groups (AEWC, BWCA and NSB) as well as independent biologists and acousticians (see Acknowledgements). MMS and project personnel also attended.

1989 Fieldwork

The main field program was conducted during May 1989 using two crews of researchers. One crew (aerial crew) conducted surveys and aerial observations of bowheads and white whales from a fixed-wing aircraft. This crew also dropped sonobuoys into the sea to document the underwater sounds near whales and other sites of interest. The second crew (ice-based crew) operated a sound projector to project recorded sounds into the sea and sound recording equipment to monitor those and other sounds. They also used a theodolite to track the movements of whales observable from the ice edge.

No open lead was present along the edge of the landfast ice NE of Barrow until 20 May in 1989, and openings in the pack ice seaward of the landfast ice edge were also scarce and small until about that date. As a result, until 20 May there was no persistent or predictable open water area, although there were transient areas of open water amidst the pack ice. Even after the nearshore lead opened on 20 May, most whales traveled through the pack ice or along the offshore side of the lead. Therefore, a suitable projector site on the pack ice had to be located each day by aerial reconnaissance. The ice-based crew spent the nights in Barrow, and used a helicopter to move to and from the chosen field location on each day when weather and ice conditions permitted.

After arriving on the pack ice each day, the ice-based crew deployed the sound projector and a monitor sonobuoy about 1 km away. Before beginning to project the drilling sounds into the sea, they recorded ambient noise levels. When the drilling sound was being projected, they monitored the transmitted sound level and recorded the noise received at the sonobuoy 1 km away. During sound playbacks, two of the ice-based observers watched for whales, documented behavioral observations, and used a theodolite to track whale movements. The highest available observation platform was usually an ice ridge, so the theodolite was only 2-5 m ASL (Above Sea Level). Because of the low elevation, most ice-based observations were restricted to whales within ~1 km of the projector. In addition, even some of the whales within a few hundred meters of the projector could not be detected because of obstruction by intervening ice.

Whales approaching the projector from greater distances were observed from a fixed-wing aircraft (Twin Otter) circling at an altitude high enough to avoid disturbing the whales (460 m ASL). The aerial observers were able to document whale movements (albeit less precisely than via ice-based theodolite), observe behavior of individual whales, determine whale distribution relative to the sound projector, and drop and monitor sonobuoys to determine sound levels at whale locations. None of these tasks could be done adequately from the ice platform when the whales were beyond ~1 km from the theodolite site.

To provide more information concerning noise attenuation in the water under different environmental conditions, three more transmission loss experiments were conducted by the ice-based crew during the main field season in May 1989. These complemented the two similar propagation tests conducted in late April 1989. These data were used in modeling studies to estimate sound levels at various distances from noise sources under different ice conditions.

1990 Planning and Fieldwork

The 1990 work was also planned in consultation with the Minerals Management Service, North Slope Borough, Barrow Whaling Captains' Association, and Alaska Eskimo Whaling Commission. In early 1990, project personnel attended a meeting in Barrow to describe the 1989 results, explain plans for 1990, and seek local advice on those plans. Results from 1989 were also presented at the North Slope Borough's "5th Conference on the Biology of the Bowhead Whale", in early April 1990. After the end of that conference, the project's Scientific Review Board met to review the draft report on 1989 work and the plans for 1990.

Because field conditions in 1989 had limited collection of data on whale reactions to *Karluk* drilling sounds and to aircraft overflights, it was agreed that additional work comparable to that in 1989 was needed. Although a recording of noise from an icebound bottom-founded caisson engaged in drilling (Hall and Francine 1990, 1991) was available to us by early 1990, it was agreed that the *Karluk* sounds should be used again in 1990. One important change that was agreed to by all concerned was that, in 1990, the sound projector could be set up as close as 15 n.mi. (28 km) beyond the northeasternmost whaling camp or 20 n.mi. (37 km) beyond the bowhead census site if there were a census.

The field approach in 1990 was essentially unchanged from that in 1989, aside from the partial relaxation of restrictions on the study area, deletion of the preliminary sound propagation test phase, and some technical improvements in equipment. Once again, there was a helicopter-supported ice-based crew and an aerial observation crew. The 1990 field season extended from 27 April to 26 May. Specific methods used in 1990 are described later (see "METHODS").

Assumptions and Limitations

A number of assumptions had to be made in designing an experimental field study that would address the general project objectives and the specific 1989 and 1990 objectives. This section lists several assumptions that may need to be made in using the results to predict the reactions of whales to actual oil industry operations. Associated with most of these assumptions are various limitations.

(1) The study area, located NE, ENE and E of Point Barrow, is assumed to be reasonably representative of locations where bowheads and white whales migrating around northern Alaska in spring might encounter oil industry activities.

> ***Limitations***: (a) All sound propagation tests and behavioral observations in 1989-90 were necessarily performed in pack ice conditions or along the south side of the pack ice (north side of the nearshore lead). The applicability of these data to whales migrating along the south side of the nearshore lead, near the landfast ice, is not verified.
>
> (b) The applicability of the 1989-90 results to the Chukchi Sea is not verified, since all 1989-90 data were necessarily obtained in the western Beaufort Sea. However, it is noteworthy that sound propagation conditions in the western Beaufort Sea during spring (this study--Richardson et al. 1990a:148) are similar to those in the Chukchi Sea during late winter-early spring (Greene 1981).
>
> (c) Water depths at many 1989-90 study locations were greater than those where bottom-founded drilling and production platforms are likely to be constructed. Water depth affects sound propagation.

(2) In order to draw conclusions about *all* whales migrating around northern Alaska in spring, it would be necessary to assume that whales visible in leads and amidst the pack ice (i.e. those studied here) react to underwater noise in about the same way as those that are not visible. The accuracy of this assumption is unknown, so we restrict our discussion (and the title of the report) to whales *visible* during spring migration.

Limitations: (a) Some whales migrate along the open nearshore lead, others through extensive leads and cracks in the pack ice, and others through closed-lead or heavy pack ice conditions. The likelihood of detecting whales differs greatly among these three habitats. Also, once detected, the likelihood of successfully observing them for a prolonged period differs greatly among habitats. Almost all 1989-90 data on reactions to noise were from whales migrating through open pack ice or along the north side of an open nearshore lead. We obtained no data on whales migrating through closed lead conditions, and very few data on whales traveling through heavy pack ice (but see 30 April 1989 results--Richardson et al. 1990a:174).

(b) Even in open pack ice, some individual whales are likely to behave in ways that make them more visible than other whales. Because observations are concentrated on the area close to the noise source, whales that come close to the source are most likely to be seen. Based on the limited observations obtainable in the difficult ice conditions encountered in 1989, we could not determine what proportion of the bowheads approached within various distances of the noise source. Based on the more extensive 1990 data collected under more favorable conditions, we consider it unlikely that many bowheads diverted around the test sites at distances beyond our effective observation radius when observing from the aircraft (see "BOWHEAD RESULTS--Larger Scale Avoidance?", p. 225). However, this conclusion comes from experiments involving playbacks of *Karluk* sounds. It would be premature to assume that there would be no long-distance reactions to playbacks of other types of sounds.

(c) Acoustic monitoring and localization methods, which have proven very valuable in studying the movements of whales migrating under the ice during spring migration past Pt. Barrow, are not nearly as useful in a study of this type. The noise emitted during playbacks would mask all but the strongest bowhead calls received near the projector site.

(3) Underwater playback of recorded underwater sounds from an industrial operation is assumed to be a useful method for evaluating the likely reactions of whales to actual industrial operations of corresponding types. In 1989-90, specifically, we assumed that playbacks of underwater sounds recorded near a drillrig on a bottom-founded ice pad were a useful method for testing the reactions of whales to an actual drilling operation of that type.

Limitations: (a) Underwater playback techniques simulate the sounds emitted by an industrial site, but exclude other stimuli to which whales may be sensitive, e.g. sight, smell, effects of physical presence on water flow. This is an advantage in the sense that it allows an assessment of the effects of noise *per se*, but a disadvantage in that the playback does not simulate all aspects of the actual industrial operation.

(b) The types of sounds available for use in this study were limited, and it is uncertain how similar the sounds from an actual drilling/production platform will be to the *Karluk* sound used here. To date, neither drilling nor production have been done in or near spring lead systems off northern Alaska. Therefore, it has not been possible to record or study the sounds emanating from such an operation. It was desirable to conduct tests of the reactions of whales to simulated industrial activities prior to the start of actual industrial activities. There is some reason for optimism that whales may react in a similar way regardless of the specific type of industrial noise used for playbacks, provided that it is continuous (Malme et al. 1984; Richardson et al. 1991). Nonetheless, any extrapolation of the 1989-90 playback results to situations involving other types of industrial sounds must be considered speculative.

(c) Sounds emitted during playbacks do not simulate the full range of sounds that an actual industrial site would emit over time. In 1989-90, we repeatedly projected a 3-minute segment of sounds emitted by the *Karluk* drillsite while it was drilling, simulating a continuous drilling operation with no interruptions. There was no attempt to simulate the noise from other activities that occur intermittently on a drillrig.

(d) Sounds emitted during playbacks do not simulate the full frequency range of sound and vibration emitted by an industrial site. Procedures used in 1989-90 provided a reasonable simulation of the components of *Karluk* sound within the 50 to 12,000 Hz band. However, the playback system underrepresented the components at frequencies below 80 Hz--especially the components below 63 Hz (see p. 88, "PHYSICAL ACOUSTICS RESULTS--Fidelity of Playbacks"). White whales are not sensitive to these low frequency components unless their levels are very high (see Fig. 100, p. 275). Hence, the inability to project them was not a problem during playback tests on white whales. It is not known whether bowhead whales are sensitive to these low frequency components. In summer, bowheads seem at least as sensitive to playbacks of drillship and dredge sounds as they are to actual drillships and dredges (Richardson et al. 1990b). This suggests that playbacks can provide relevant data.

(4) It is assumed that the presence of the observers did not bias the results significantly. Three potential problems existed (see items a-c, below), but these sources of bias were present during most control observations as well as during playbacks. Furthermore, the potential for bias of all three types is believed to be limited.

Limitations: (a) Whales are known to react to aircraft overflights in some situations; many of the 1989-90 observations were obtained from an aircraft circling above the whales. Studies in summer and autumn have shown that an observation aircraft circling over bowheads causes no significant disturbance reaction provided that it remains at an altitude of at least 460 m (1500 ft) at a low power setting, and avoids passing directly over the whales (Richardson et al. 1985a,b). Anecdotal data suggest that white whales also tolerate aircraft at that height (reviewed by Richardson et al. 1991). Limited data from this 1989-90 study suggest that sensitivity to aircraft is no greater in spring than during summer or autumn (see p. 264 and 282). Given this, and the fact that we excluded observations from periods when the aircraft was below 460 m, the presence of the aircraft is not considered to be a significant problem.

(b) The projected drillsite noise came from a small camp located on the edge of an ice pan. This camp, including the ice-based personnel, may have been visible to some of the closer whales while they were at the surface. However, reactions to visual cues would be minimized by the small size of the ice-based operation, the limitations of vision through the air-water interface, and the frequent presence of visual obstructions (ice floes) between the camp and the whales. Also, interpretation problems arising from any non-acoustic effects that do exist can be minimized by comparing behavior of whales passing the camp when the projector is operating vs. silent. This type of control was applied during the 1990 field season.

(c) It was necessary to use a small gasoline-powered generator at the ice camp during playbacks and some control periods. This emitted underwater noise. This noise was detectable underwater within a few hundred meters of the campsite during control (quiet) periods, but the generator noise was masked by the projected sound during playbacks (see p. 98). The possibility of close-range reactions to generator noise during control periods is discussed later (p. 244, "BOWHEAD RESULTS--Non-Playback Effects of Ice Camp"). That section concludes that *(i)* there may be some short-range responses to acoustic or non-acoustic cues from the camp itself, but *(ii)* these cannot explain the more pronounced responses observed during projection of industrial noise than when the projector was off. This difference must have been caused by the sound playbacks themselves.

(5) It is assumed that disturbance of whales is evident by visual observations of their distribution and movements near the noise source, and (for bowheads) visual observations of the details of their individual behaviors. Previous studies have shown that bowhead and white whales often react in visually observable ways when subjected to strong noise from actual or simulated oil industry operations.

Limitations: (a) Even the most conspicuous whales are visible for only a fraction of the time--typically less than 20% in migrating bowheads. Whales migrating past a disturbance source are often below the water and invisible when at their closest point of approach. During periods while whales are underwater or under ice, it usually is not possible to observe them directly. However, some aspects of their movements underwater or under ice often can be inferred from their diving and re-surfacing positions, headings, and times. Also, migrating whales occasionally travel at sufficiently shallow depths such that they can be seen below the surface throughout part or all of a dive in open water. This was common on some days in 1990, including the playbacks on 11, 13 and 16 May 1990.

(b) The calling rates of whales could not be compared under playback vs. control conditions. Some other studies of whales have suggested, often based on equivocal evidence, that call rates diminish in the presence of man-made noise. This could not be studied here because the majority of the calls heard in the absence of projected noise would be undetectable due to masking even if they were present during playbacks.

(c) No direct measure of physiological stress is possible during field observations of passing whales. However, in the case of bowheads, surfacing, respiration and diving cycles were monitored quantitatively. These variables may provide indirect and limited indications of stress. These variables could not be observed reliably for white whales, so we had no similar indicator for that species.

(d) No data of any type could be collected on any whales that avoided detection, e.g. by remaining amidst heavy ice. This was not considered to be a significant problem in 1990 (see limitation 2b, above).

(e) This study concerns the short-term reactions of migrating whales to one source of industrial noise. The long-term consequences with respect to the well-being of individuals and the population are not addressed directly. However, data on the short-term reactions to one noise source may provide an indication of the likely severity of the long-term effects of one or more sources of that type of noise.

STUDY AREA, WEATHER AND ICE

Selection Criteria

In choosing a study area, it was necessary to compromise between choosing (a) an area where many whales would be encountered and (b) an area where project activities would not interfere (or be perceived to interfere) with native subsistence whaling or other scientific studies.

Local Concerns

This study could not have been conducted if it had been opposed by local organizations such as the North Slope Borough, the Alaska Eskimo Whaling Commission, or the Barrow Whaling Captains' Association. Strong opposition would have occurred if the proposed study site were southwest of the northeasternmost of the spring whaling communities (Barrow). Whalers would have been strongly concerned about a proposed disturbance experiment anywhere "upstream" (south or southwest) of any whaling site. They would have been concerned that such a study might block the passage of some whales, or interfere with the subsequent timing or route of the whale migration past the whaling community. For the same reasons, the study area could not have been near Barrow itself.

In addition, for more than a decade there has been an annual spring bowhead census near Pt. Barrow. In 1988, a very intensive census effort was conducted, and in 1989 a scaled-down census effort was planned for late April and May. A minor effort was planned again for 1990 but no work was actually conducted in 1990. This census at Barrow has been very important to the local people, to U.S. regulatory agencies, and to the International Whaling Commission. The census procedures have become very precise and highly sophisticated. Present census and data analysis procedures depend on the consistent migratory behavior of the whales. Disturbance-related changes in whale behavior might include changes in swimming speeds, average distance from the ice edge, or whale headings. Changes in any one of these behaviors could significantly affect the results of the census. Also, acoustic monitoring techniques are now an important part of the census. If background noise levels were elevated because industrial sounds were being projected into the water nearby, the range of effective acoustic monitoring (and especially of call localization) would be reduced. Any real or potential interference with the census would have been unacceptable to a variety of local, national, and international interests.

Given these considerations, the project would not have received local acceptance if the proposed field site were anywhere near or southwest of Barrow. Locations well to the east of Pt. Barrow appeared to be the only locations that might be acceptable to local people and to agencies concerned about the whale census.

Specific Study Location

As part of the planning process for this study, Miller (1989) reviewed the available information on ice conditions and on whale distribution in the area east and northeast of Pt. Barrow during spring. Results of this review are summarized in Richardson et al. (1990a:2-12). Logistically, the most advantageous location for the study area and ice camp was expected to be along the landfast ice edge where a semi-permanent camp might be established. However, the literature reviewed by Miller (1989) indicated (and our 1989 and 1990 studies confirmed) that few whales are found along the landfast ice edge more than about 35 km east of Barrow. Beyond that distance, most whales have moved offshore into the seaward side of the nearshore lead or into the pack ice beyond the nearshore lead.

Thus, during most years, the best location for the sound projector would be along the landfast ice edge within 35 km of Pt. Barrow. Given that such a site might be too close to whaling and census areas, LGL recognized from the start of the planning process that the projector might have to be set up on pack ice northeast of Pt. Barrow. However, the whale migration corridor widens as the whales travel east of Pt. Barrow, reducing the numbers of whales expected to pass close to any given site. Also, logistic support becomes progressively more difficult with increasing distance to the east.

Given the above, it was desirable to work as close to Barrow as possible without causing real or perceived interference to whaling and to the census. The most appropriate distance east of Barrow was determined through an acoustic modeling study (Malme et al., p. 261-284 *in* Richardson et al. 1990a) and consultation with local Barrow organizations, individuals and scientific investigators. In 1989, to provide convincing "safety" margins and to avoid opposition from the various concerned groups, we selected an area about 60 km (32 n.mi.) NE or ENE of Pt. Barrow as the approximate location for the industrial noise playback experiments. We also undertook not to fly within 10 km of the census or whaling sites (unless these were within 10 km of Barrow's airport).

The 1989 study showed that we could conduct the work without interfering with other groups. Therefore, in 1990, after consultation with the same groups, it was agreed that we could work closer to Barrow. In 1990, it was agreed that our projector sites would be at least 15 n.mi. (28 km) northeast or east of the northeasternmost whaling camp. At any times when the bowhead census crew was working on the ice, we undertook to keep the projector at least 20 n.mi. (37 km) away. In addition, we again undertook not to fly within 10 km of the whaling or census sites except as necessary to take off or land at Barrow. The reduced distance limit in 1990 proved to be very helpful in providing more flexibility in choice of projector sites.

Ice Conditions

Sea ice dominates the Alaskan Beaufort Sea, with ice cover of almost 100% for 9 to 10 months each year (Norton and Weller 1984). There are three principal zones of ice cover in the Beaufort Sea: landfast ice, the shear zone, and the pack ice. A brief description of these zones and the annual variation in their occurrence can be found in Richardson et al. (1990a:28-29).

1989 Ice Conditions

Ice conditions in 1989 were more closed than in typical years. When the study was initiated in late April, no major lead was present either along the fast ice edge or in the area where the E-W offshore shear zone usually forms. The overall ice cover was 98 to >99%. The few open water areas consisted of small holes between ice pans, plus narrow cracks and leads that tended to be oriented NW to SE. These general ice conditions were maintained until 12 May, when winds began to shift the offshore pack ice and formed several minor offshore leads oriented SW to NE through the pack ice. Ice conditions remained about the same until 20 May, when a major nearshore lead formed across our study area. Thereafter, the landfast ice was separated from the offshore pack ice by a broad lead. That lead remained open for the remainder of the 1989 study period. The 1989 ice conditions are described in detail in Richardson et al. (1990a:29-32).

1990 Ice Conditions

Ice conditions in 1990 were similar to those in the typical years that are described in Richardson et al. (1990a:28-29). When the study was started in late April, there was a narrow nearshore lead along the fast ice edge ENE of Barrow. Little open water was present amidst the offshore pack ice north and NE of Barrow. The lead started to open at Barrow on 7 May, and was several kilometers wide by 10 May. This major lead extended across much of our study area (Plates 1 and 2). The pack ice north of the lead was generally heavy, but there were localized corridors of less-dense pack ice, especially in the first few kilometers north of the main nearshore lead.

The major nearshore lead and the pack ice farther offshore remained more or less unchanged until 20 May when strong winds moved the offshore pack ice. The lead near Barrow widened but the lead became choked with ice ~40 km ENE of Barrow. During the final few days of the 1990 study, strong winds altered the lead and pack ice conditions almost daily. The lead along the fast ice edge was reduced to 1 km in width by 25 May, and secondary leads developed in the pack north of Barrow.

Weather

The typical weather conditions at and near Barrow during spring were described by Richardson et al. (1990a:32-43). That document also describes the weather in the study area in 1989. In summary, weather and associated ice conditions in 1989 were worse than normal for conducting bowhead whale studies. Weather was clear at the end of April and in early May in 1989, but little open water was present so whales could not be studied very effectively. Unusually cold weather from 5 to 8 May 1989 (Fig. 2) froze existing open water areas and consolidated the offshore pack ice, making observations even more difficult. From 10 to 26 May 1989, low ceilings, snow and fog prevented aerial observations from altitude 460 m ASL most of the time. Observing conditions were ideal on 27-30 May 1989, but most bowheads had already migrated past Barrow by that time.

Weather conditions near Barrow in the spring of 1990 were much more amenable to a study of this type. During the last few days of April and the first six days of May, temperatures at Barrow were near normal (Fig. 3). However, during the remainder of May temperatures were consistently above normal, and "record" high temperatures[3] were recorded or equalled on several different days (Fig. 3). The Twin Otter crew was able to conduct surveys on similar proportions of the days in 1989 and 1990. However, cloud ceilings were much better in 1990. None of the 29 behavior observation sessions conducted in 1990 had to be conducted at altitudes <460 m, whereas in 1989 four of 17 sessions were conducted at <460 m, and other sessions were not initiated because of the prevailing low cloud. Because all 1990 observation sessions were from altitude 460 m, none of our 1990 aerial observation data were confounded by potential Twin Otter aircraft disturbance, contrary to the situation in 1989.

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[3] Historical weather data against which 1990 data are compared are for the 1951-1980 period. Hence, some of the supposed record high temperatures were not true record highs.

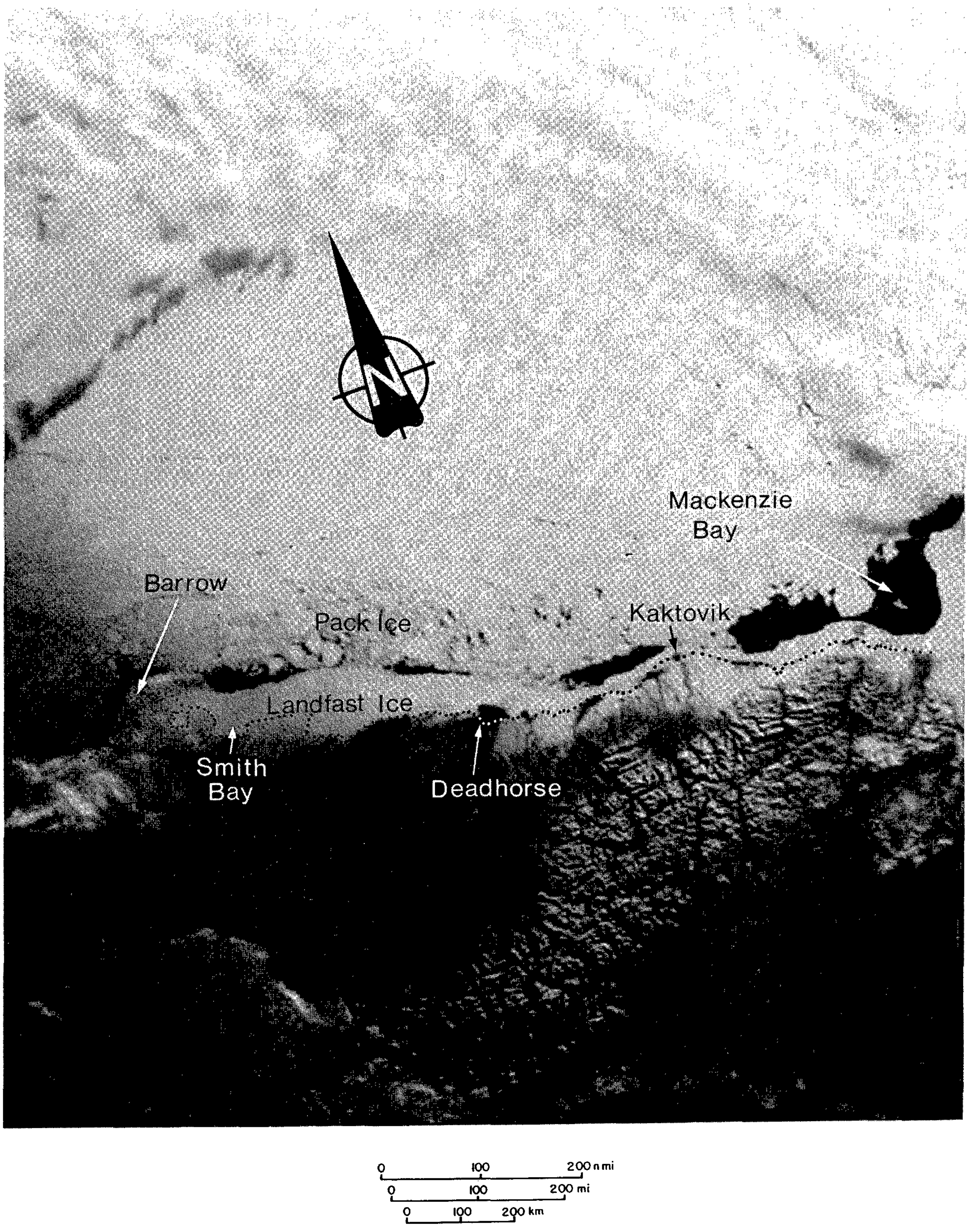

Plate 1. NOAA satellite imagery of the Beaufort Sea, 19 May 1990, showing a well-developed nearshore lead and extensive offshore pack ice.

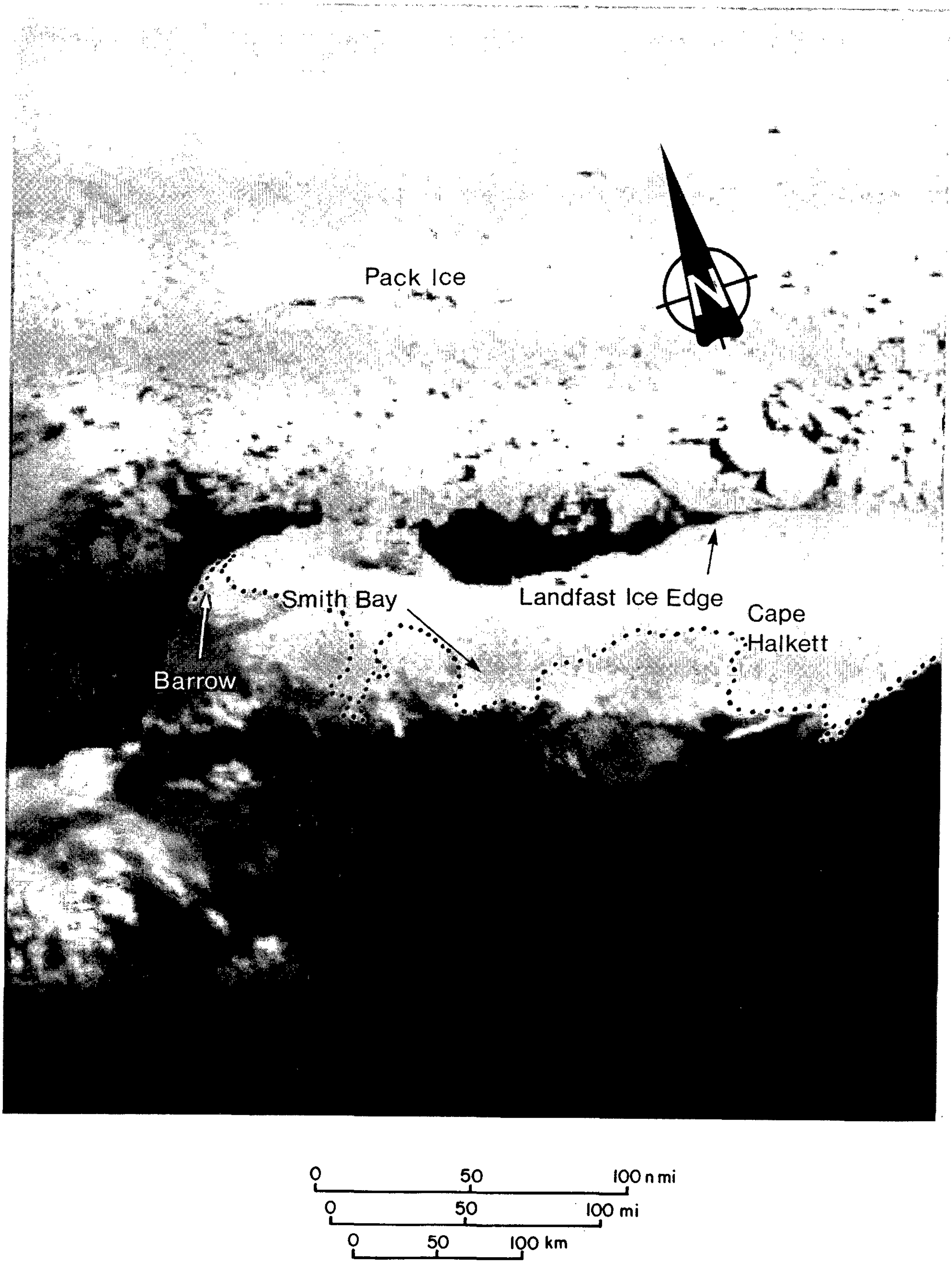

Plate 2. NOAA satellite imagery taken of the western Beaufort Sea, 19 May 1990, showing the landfast ice edge, nearshore lead, and offshore pack ice near Barrow, Alaska.

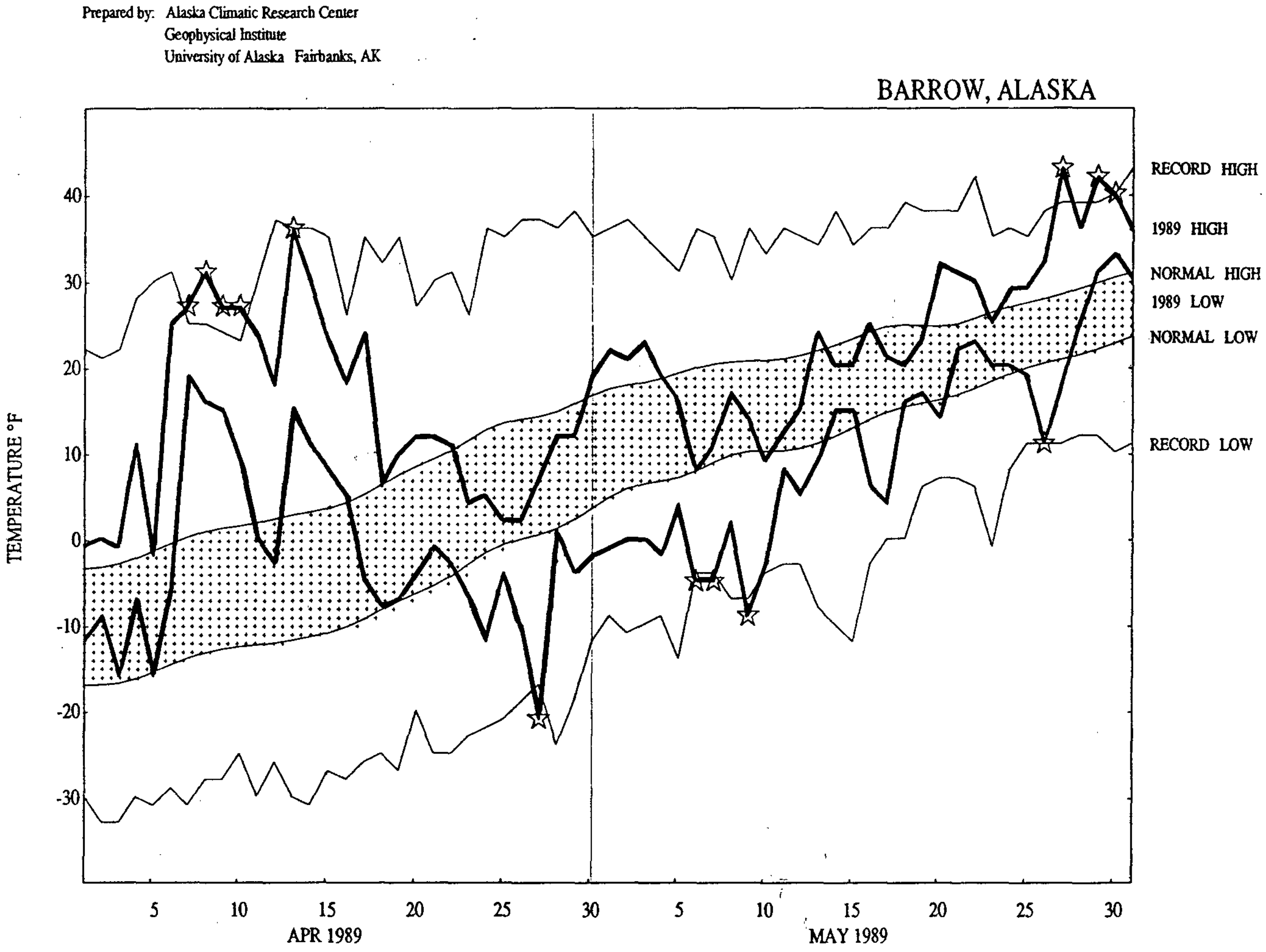

FIGURE 2. Daily weather in April and May 1989 at Barrow, Alaska. Normal and record highs and lows are based on data collected from 1951 to 1980. Stars show occasions in 1989 when the temperature was outside the range for 1951-80.

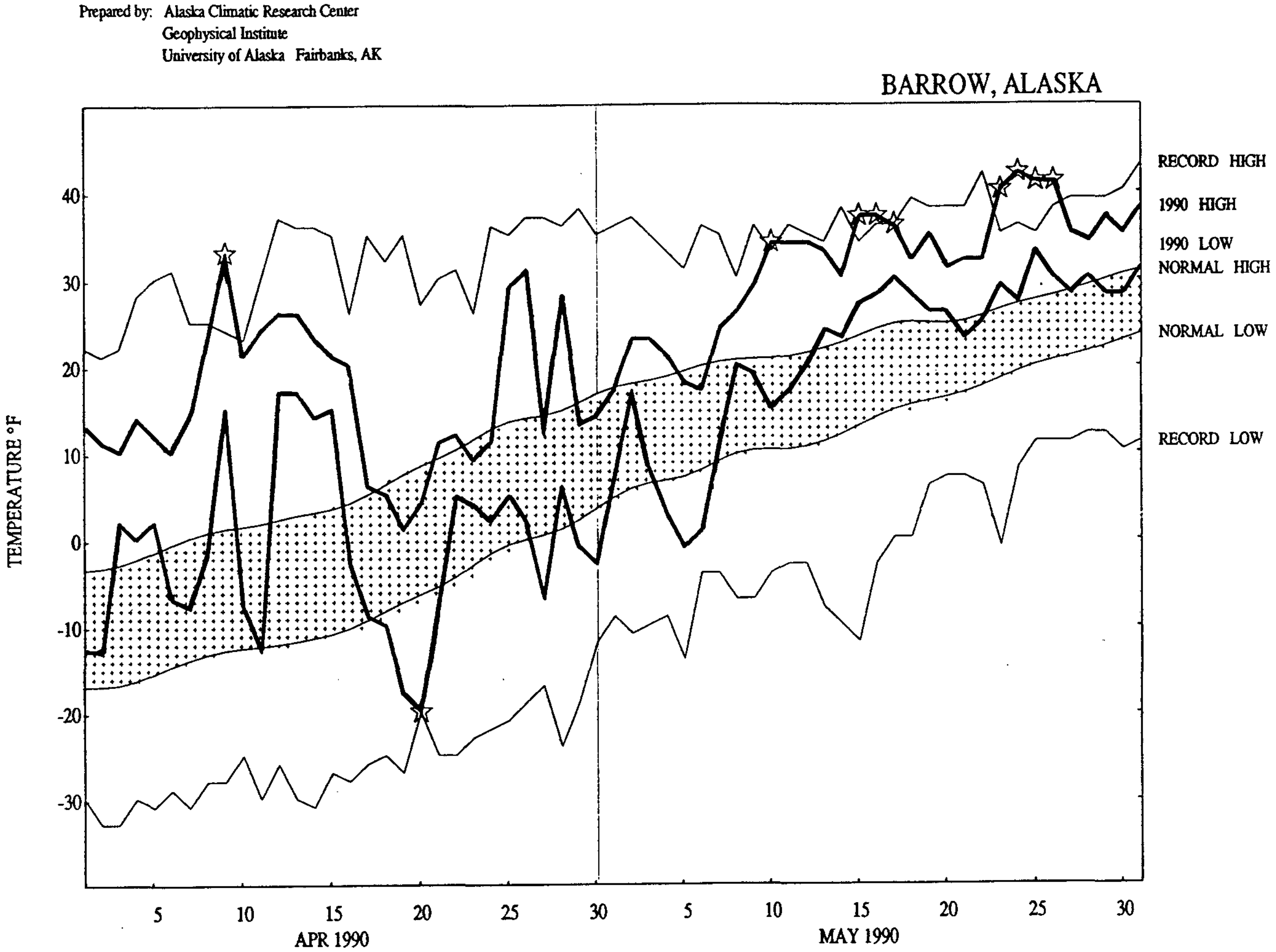

FIGURE 3. Daily weather in April and May 1990 at Barrow, Alaska. Normal and record highs and lows are based on data collected from 1951 to 1980. Stars show occasions in 1990 when the temperature was outside the range for 1951-80.

METHODS

Physical Acoustics Methods

This section is organized according to the four specific 1990 field objectives concerning, in whole or in part, physical acoustics (see p. 5-6). Those objectives were as follows:

(1) ***Ambient Noise.*** To measure ambient noise levels and characteristics in leads and cracks along the spring migration corridor of bowhead and white whales in the western Beaufort Sea, including infrasonic components.

(2) ***Transmission Loss.*** To measure and model transmission loss of underwater sound along that part of the spring migration corridor, based on playbacks of (a) test tones at selected frequencies between 50 Hz and 10 kHz, and (b) continuous drilling platform sound (*Karluk* sounds).

(3) ***Playback Experiments.*** To measure the short-term behavioral responses of bowheads and (as possible) white whales visible in open water areas along their spring migration corridor in the western Beaufort Sea to underwater playbacks of continuous drilling platform sound (*Karluk* and CIDS sounds).

(4) ***Infrasonic Noise.*** To collect some of the data needed to assess the importance of the infrasonic components (<20 Hz) of industrial noise; specifically, measure ambient noise at infrasonic frequencies and determine whether bowhead calls contain infrasonic components.

Ambient Noise

Methods for measuring ambient noise in 1990 followed the practices begun in 1989, with one major improvement: use of Digital Audio Tape (DAT) recorders.

The ice-based crew recorded background noise (1) at the projector site immediately before and after each playback period, and (2) at each receiving station during each sound propagation experiment. The aircraft crew also recorded background noise via sonobuoys dropped at times or places when projected industrial noise was not present. The ice-based crew also recorded some sonobuoy signals. In assessing a recording as suitable for inclusion in the ambient noise database, we excluded recordings with known man-made sounds (aircraft, generator, and playback sounds). We included recordings with bowhead, white whale and seal calls, which are natural environmental sounds.

The ice-based crew used one type of hydrophone for ambient noise measurements: the ITC 6050C. This hydrophone includes a preamplifier next to the hydrophone. The preamplified signals were further amplified by a postamplifier with 0-60 dB gain (selectable in 10 dB steps) before being recorded. Most tape recording was via a TEAC model RD-101T digital audio tape (DAT) recorder suitable for 0-20,000 Hz; a "memo" channel permitted voice announcements by the operator without interrupting the acoustic data. The TEAC also provided a continuous record of date, time, time from the start of the tape, and event number. Sometimes a Marantz PMD430 audio cassette recorder was used (calibrated 10-10,000 Hz).

The aircraft crew used sonobuoys of three types: *(1)* AN/SSQ-41B, with omnidirectional hydrophone, effective at 10-20,000 Hz, hydrophone depth 18 m. *(2)* AN/SSQ-57A, with calibrated omnidirectional hydrophone, effective at 10-20,000 Hz, hydrophone depth 18 m or 14 m. (The standard depth is 18 m, but some units had been modified to deploy their hydrophones to depth 14 m, for use in shallow water.) *(3)* AN/SSQ-53B DIFAR (directional) sonobuoys, effective 10-2400 Hz, hydrophone depth 27 m. The radio signals from all types of sonobuoys were received at a dedicated antenna on the project's Twin Otter aircraft, amplified by a low noise RF preamplifier, and split to two Regency MX5000 wideband FM receivers. The two receivers permitted simultaneous recordings of the underwater sounds from two sonobuoys. The Regency receivers had been modified by adding an audio amplifier attached to the FM discriminator output. This amplifier had a flat audio response from 1 to 20,000 Hz. The special audio amplifier output signals were tape recorded on a second TEAC model RD-101T DAT recorder.

The ice-based crew used a similar setup to record sonobuoy signals but they used a Kenwood model RZ-1 wideband FM receiver to tune the sonobuoy channels. The Kenwood radio had been modified with the same audio frequency amplifier to provide a flat response from 1 to 20,000 Hz.

Samples of ambient noise were analyzed using Greeneridge's standard power spectrum analysis methods as applied in previous projects, including the 1989 phase of this study (Richardson et al. 1990a). The calibration range and analysis frequency range extended down to 5 Hz and up to 8000 Hz as appropriate to the sensor used. A summary of the power density spectrum analysis characteristics is as follows:

- Sample rate: 16,384 samples/second.
- Fourier transform block size: 8192 samples (0.5 s, 2 Hz bin spacing).
- Blackman-Harris minimum 3-term window applied (3.4 Hz bin width).
- 50% overlap of transform blocks.
- 8.25 seconds of data per analysis; based on averaging of transform blocks.
- Spectrum levels computed and graphed.
- 1/3rd octave and 20-1000 Hz band levels computed.

The computed results were adjusted based on the individual calibration curves for the specific pieces of equipment used in receiving and recording the signals: hydrophones, amplifiers, sonobuoys, sonobuoy receivers, tape recorders, filters, and analog-to-digital converters. Data originating from sonobuoys were corrected to allow for the strongly sloped frequency response curves of sonobuoys. This was done using either the individual calibration curve for a particular sonobuoy (57A buoys) or, where necessary, the standard curve for a given class of sonobuoys (41B and 53B buoys). For all three types of sonobuoy, sensor sensitivity is specified to be within ±2 dB of a standard value at one frequency (100 Hz).

One-third octave band levels of the ambient noise were summarized on a percentile basis. The broadband 20-1000 Hz band level was also plotted over time over the duration of the 1990 field season.

Each ambient level value derived by this method is an average over 8.25 s. The project's Scientific Review Board (SRB) also recommended investigating the shorter-term variability of the ambient noise. This would show whether there were short periods of time (<8.25 s) during which the noise level was significantly lower than the measured average level. If so, whales might, at times, be able to hear weak sounds from distant sources--sounds with received levels lower than the average ambient noise. The characteristics for short-term analyses were

- Sample rate: 2048 samples/second.
- Sample block size: 122,880 samples (1 minute).
- Block sizes for acoustic power computation: 512 and 17,408 samples (0.25 and 8.5 s).

Several methods of summarizing and presenting these data are described under "PHYSICAL ACOUSTICS RESULTS--Short-term Ambient Noise" (p. 55*ff*).

Transmission Loss

The objectives of the transmission loss (TL) measurements and modeling in 1990 were essentially the same as in 1989, and the field methods were also similar. Measurements were carried out on four days in 1990: May 1, 2, 24, and 25. We installed a J-11 underwater sound projector at a base camp. Figure 17 (p. 64) shows the locations of the four base camps and their associated receiving stations. The projector was suspended at a depth of 18 m below the edge of an ice pan. The projector's audio amplifier (250 W Bogen MT250) was powered by a 2.2 kW gasoline-powered Honda generator sitting on snow-covered ice, typically about 20 m back from the ice edge.

A cassette tape had previously been recorded with the sounds for transmission. We used three types of sounds in each of the first three transmission tests: tonal sweeps, pure tones, and sounds from the drillrig on a bottom-founded ice-platform at *Karluk*. We added a fourth sound segment for the final TL test--supply ship *Robert Lemeur* icebreaking. *(1)* The tonal sweeps were special "hyperbolic frequency modulation" (HFM) signals (Rihaczek 1986) synthesized by BBN Systems and Technologies Corp. Each 5-s sweep spanned one-third octave at a center frequency of 50, 100, 200, 500, 1000, 2000, or 5000 Hz. During each transmission, each sweep was sent four times with no pauses between sweeps. *(2)* The pure tones were at frequencies 50, 100, 200, 500, 1000, 2000, 5000, and 10,000 Hz. Each tone was transmitted for 20 s with 5 s between tones. *(3)* The *Karluk* drilling noise segment was 35 s long. *(4)* The *Robert Lemeur* segment was 44 s long. Characteristics of the *Karluk* and *Robert Lemeur* sounds were described by Richardson et al. (1990a:80-86). Each transmission of these 3 or 4 types of sounds lasted ~8 min, and the operator rewound the tape after each transmission ended.

The projected sound was monitored with an ITC model 1042 spherical hydrophone placed at a nominal distance of 2 m above the projector face. The actual distance was measured during each deployment of the J-11. The monitor hydrophone signal was tape recorded on a Marantz model PMD430 audio cassette recorder. The recordings were analyzed with the usual Greeneridge power spectrum analysis technique. The resulting levels were adjusted, assuming spherical spreading, to estimate the source level at a reference distance of 1 m. The waveform was monitored on an oscilloscope during projector operation to assure linear operation. The overall source level depended on the frequency content of the signal. It was typically near 166 dB re 1 µPa-m in 1990, vs. 165 dB in 1989.

The receiving/recording equipment consisted of an ITC model 6050C hydrophone, a postamplifier with 0-60 dB selectable gain, and a TEAC model RD-101T digital audio tape (DAT) recorder operating from a battery. The receiving station crew used a Rolotape distance measuring wheel to locate receiving sites along the edge of the ice floe at ranges 100, 200 and (if possible) 400 m from the J-11 projector. At each receiving station, the hydrophone was deployed on a faired cable to depth 18 m. Ambient noise was recorded first. The remote crew then radioed the base camp to request transmission of the taped signals. When transmissions ended, ambient noise was again recorded. At the short-range stations (≤400 m range), the ambient noise was recorded both with and without operation of the generator at the base. This was done to determine the characteristics and range of detectability of the underwater components of the generator sounds.

The distant receiving stations were reached by helicopter. The crew attempted to find suitable recording stations at ranges 0.5, 1.0, 2.0, 5.0, and 7.5 n.mi. A suitable site was one along the edge of an ice floe bordered by open water or thin recently-refrozen ice. The helicopter's GNS-500 VLF navigation system was used for positioning. The GNS was not designed for such precise navigation. However, GNS readouts of the relative positions of two stations overflown at short intervals normally are accurate within a few hundred meters. When there was doubt about the accuracy of the GNS, the helicopter returned to the ice camp in order to re-calibrate the GNS. This was also helpful in allowing for the rapid drift of the ice (and thus the projector) on some days. The absolute position of the ice camp was determined more accurately using a Si-Tex model A-310 satellite navigation system. At the most distant stations, beyond hand-held radio range, the base camp crew operated the projector on a timed schedule and the remote crew sometimes recorded two transmission cycles. Water depth at each receiving station was measured with an echosounder.

Transmission loss (TL) was determined for each receiving station, sound type, and frequency. In the case of the *Karluk* and *Robert Lemeur* sounds, TL was determined for each 1/3-octave where there was significant sound energy. TL for each test sound or 1/3-octave band was found by *(1)* determining the received level (RL) via analysis methods similar to those used for ambient noise, and then *(2)* subtracting RL from the 1-m source level of the corresponding signal as determined via the monitor hydrophone near the projector.

The TL data from each test were used in regression analyses to determine an equation for TL vs. range for each frequency in the area of each test. Each regression analysis included the TL measurements based on all 3 or 4 sound types listed above--HFM sweeps, pure tones, *Karluk* and (test 4 only) *Robert Lemeur*. The fitted equations were of the general form

$$TL = A + B*R + C*\log_{10}(R)$$

where R is in kilometers but TL is the transmission loss in dB referred to range 1 m. The TL value for range 1 m (always 0 dB) was not used in the regression analysis because the equation is not appropriate for ranges less than 100 m. These equations can be used to predict TL from the source to distances ranging from ~100 m through 10 km (the approximate range of the data). ***The equations cannot be used to predict TL from the source to distances less than ~100 m.***

Coefficient C, applying to the logarithmic function of range, is expected to be near 10 for shallow water (cylindrical spreading), near 20 for deep water or very short ranges (spherical spreading), and about 15 for intermediate cases, depending also on source and receiver depths. Coefficient B, applying to the linear function of range, is determined by the combined effects of sound absorption and sound scattering; B must be positive. The constant A, added to B, provides the transmission loss value between 1 m and 1 km. As a rough estimate, we would expect the loss at 1 km to be less than 60 dB [$20*\log_{10}(1000)$] because spreading loss would be spherical for short ranges, transitioning toward cylindrical by range 1 km.

This type of generalized regression equation was fitted to the data for each frequency separately for each 1990 TL test. Then the process was repeated with preselected values of C--10, 15 and 20--on the assumption of cylindrical, intermediate or spherical spreading (respectively) within the distance range for which we had data. The results were assessed in terms of goodness-of-fit and physical appropriateness, given the known water depths. The most appropriate fitted equations were graphed, along with the individual data points, and were used to tabulate estimates of TL vs. range and frequency at the four test sites.

Playback Experiments

All playback experiments in 1990 used the same recording of *Karluk* drilling noise as had been used for the 1989 experiments. Consideration was given to switching to drilling sounds recorded near the CIDS Concrete Island Drilling System by Hall and Francine (1990). However, it was decided that it would be preferable to obtain a more adequate sample size of whale observations in the presence of the sound type used for playbacks in 1989--the *Karluk* sounds. Also, there were doubts about the appropriateness of the available recordings of CIDS sounds for use in playback experiments.

Playback Procedures.--The playback experiments in 1990 were conducted in a manner similar to that in 1989, but with a slightly higher source level. During all playback experiments, we projected underwater sounds that had been recorded 130 m from Chevron's *Karluk* ice-founded drillrig in March 1989 (Richardson et al. 1990a:80*ff*). A model J-11 underwater sound projector was suspended over the ice edge at depth 18 m. An ITC model 1042 spherical hydrophone was mounted 2 m above the projector face to monitor the signals projected. A 250 W Bogen MT250 amplifier drove the J-11. A Sony TC-D5M cassette recorder played a 3-min loop tape of the continuous *Karluk* sounds. A Marantz PMD430 audio cassette recorder was used to record the monitor hydrophone signal and signals received from a sonobuoy deployed ~1 km away.

One specific objective of the 1990 field work was to project effectively the components of drilling sounds above 20 Hz (p. 6). The limitations of the J-11 projector and other practical broadband projectors prevented meeting this objective as completely as desired. The J-11 and other practical projectors cannot reproduce infrasonic components of industrial sound, i.e. components at frequencies below 20 Hz. Also, between 80 Hz and 20 Hz, the J-11 reproduces recorded sound progressively less well with decreasing frequency. Between 80 and 50 Hz, the recorded sound is reproduced, but at a proportionately lower level than that at frequencies above 100 Hz. Below 50 Hz, there is little effective output from the J-11 (see "PHYSICAL ACOUSTICS RESULTS--Fidelity of Playbacks", p. 88). In 1990, the field crew drove the J-11 with slightly stronger power levels than in 1989. The result was slightly higher source levels at all frequencies. However, sound components at frequencies below 80 Hz were proportionately underrepresented, and those at frequencies below 63 Hz were seriously underrepresented. In 1991, a J-13 projector was used in an attempt to improve performance at low frequencies.

Measured Sound Levels During Playbacks.--Sonobuoys deployed by hand and by aircraft were used to monitor the levels and characteristics of the projected *Karluk* sounds as received at different distances from the projector, including near whales.

A sonobuoy was installed manually at a nominal distance of 1 km from the projector prior to each playback of drilling noise. The helicopter was used for transportation to this site. Usually we used a Sparton Defense Electronics AN/SSQ-41B wideband sonobuoy modified to use external batteries for longer life. Also, its cutoff circuits had been disabled to allow operation for more than the usual maximum of 8 h. Hydrophone depth was 9 m. On some days, we used a Sparton AN/SSQ-57A sonobuoy that was standard except that the hydrophone depth was 14 m. Both types of sonobuoys provided useful data from 10 to 20,000 Hz.

Sounds received by each of these types of buoys were telemetered on VHF frequencies between 162.25 and 173.5 MHz. A calibrated Kenwood model RZ-1 wideband FM receiver, modified for flat audio response from 1 to 20,000 Hz, was set up at the base camp to monitor the sounds received at the manually-deployed sonobuoy. A low-noise RF preamplifier was positioned at the antenna to improve weak RF signal reception. The same telemetered sonobuoy signals were often received and recorded aboard the project's Twin Otter aircraft. Sounds projected during playback experiments were monitored and recorded with this remote installation. This provided received level data at one known range (~1 km) in addition to the known level at the projector.

Sonobuoys were dropped from the Twin Otter aircraft, usually at locations near whales, during playback experiments and at certain other times. This allowed us to measure the levels and spectral characteristics of sounds reaching whale locations. It also allowed us to monitor whale calls. We used Sparton AN/SSQ-57A sonobuoys with standard hydrophone depth 18 m or modified depth setting 14 m. DIFAR sonobuoys, Sparton model AN/SSQ-53B, were also used. These directional sonobuoys employ sensors at depth 27 m and span the frequency range 10-2400 Hz. Signals from all types of sonobuoys were received via a dedicated antenna on the Twin Otter. A low-noise RF preamplifier preceded two calibrated Regency MX5000 wideband FM receivers. They had been modified for flat audio response from 1 to 20,000 Hz.

The approximate distances of the manually-deployed and air-dropped sonobuoys from the ice camp were determined via the helicopter's and Twin Otter's GNS navigation systems. Distances to sonobuoys within ~1.5 km of the ice camp usually could be checked via theodolite sightings of the sonobuoy from the base camp or by measuring the acoustic travel time from projector to sonobuoy. Travel time could be measured when signals from the monitor hydrophone (~2 m from projector) and sonobuoy were recorded simultaneously on the same recorder at the base camp. When two sonobuoys were monitored simultaneously, as was sometimes done from the aircraft, their relative distances from the projector were measured based on the difference in arrival times of projected sound components at the two buoys.

Sound Levels Received by Whales During Playbacks.--Equations to predict received levels vs. distance were developed for each playback test. These equations were based on (1) measured sound levels during that test and (2) transmission loss models derived from the four TL experiments during 1990.

Measured water depths at the playback sites influenced the choice of equation. In the shallowest water, i.e. depth <50 m, a spreading loss term of 10*log(R) corresponding to cylindrical spreading was appropriate. For depths 50 to 200 m, an intermediate spreading loss term of 15*log(R) was appropriate. For depths >200 m, spherical spreading--represented by

20*log(R)--was assumed to apply. These depth zones were selected after examining the measured received levels vs. range during disturbance and transmission loss tests.

Two or three frequency bands were considered when describing sound exposure: *(1)* The 20-1000 Hz band, which included all significant energy from the *Karluk* playback.[4] *(2)* The one-third octave band centered at 200 Hz, which was generally the strongest one-third octave band in the *Karluk* spectrum. Occasionally, due to frequency-dependent propagation effects, the level in the one-third octave band centered at 160 or 250 Hz was slightly stronger than that near 200 Hz. In these cases, the band around 160 or 250 Hz was considered. *(3)* For the first disturbance test on 13 May, the one-third octave band centered at 1250 Hz was also considered. The first J-11 projector used on the 13th had developed a slow leak. Its output level gradually decreased and signal distortion increased. For part of this period the one-third octave band near 1250 Hz contained the strongest projected sounds. The adjacent one-third octave bands, centered at 1000 and 1600 Hz, were also considered in determining the strongest received levels during the first test on the 13th.

The specific procedures used to develop suitable transmission loss models for each playback day are described in Appendix B. Different procedures were used on different days, depending on circumstances and the available data. During the analyses and computations, all sound levels were specified to the nearest 0.1 dB re 1 µPa. For presentation in tables, the results are rounded to the nearest integer dB.

For each playback test, the sound levels in the above-described frequency bands were calculated as functions of range. Estimated sound levels based on transmission loss models were graphed in relation to distance from the projector. These estimates were tabulated for standard distances of 0.2, 0.5, 1.0, 2.0, and 4.0 km, and for the distances of closest approach by bowheads. Average measured ambient noise levels were also tabulated to permit assessing the signal-to-noise ratios. It should be noted that the ambient levels varied by as much as 20 dB during measurements on any given day.

Infrasonic Components of Ambient Noise and Bowhead Calls

Because of concerns about the possibility that bowheads are sensitive to frequencies lower than those that can be reproduced adequately by the J-11, we wanted to obtain information concerning the sources, transmission and reception of sounds at low frequencies, including infrasonic frequencies (<20 Hz). Of the several possible avenues of investigation, two were practical in 1990. We measured the infrasonic components of the natural ambient noise, and we undertook a preliminary assessment of bowhead calls to see if they included infrasonic components. *(1)* The levels of ambient noise at infrasonic frequencies are relevant to any attempt to evaluate how far away an infrasonic component of an industrial noise might be audible above the natural background noise at corresponding frequencies. *(2)* If bowhead calls contain infrasonic components, there would be increased reason for believing that bowheads can hear those frequencies.

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[4] The original *Karluk* sounds included components below 20 Hz, but these were not reproduced during playbacks via the J-11 projector.

In measuring ambient noise levels, the methods used for the sonic frequency range were also used for the lower frequencies. The calibrations and analyses were extended to 10 Hz for the sonobuoys and 5 Hz for the ITC 6050C signals. This permitted inclusion, in the ambient noise statistics, of band levels for third-octave bands centered at 12.5 and 16 Hz.

Waterfall spectrum analysis was used to examine bowhead calls for infrasonic and other low-frequency components. This approach is useful in determining whether, at the times when bowheads emit their known types of calls, there are also infrasonic components that have not previously been recognized. The characteristics for waterfall spectrum analysis were as follows:

- Sample rate: 1024 samples/second.
- Fourier transform blocksize: 1024 samples (1 Hz bin spacing).
- Blackman-Harris minimum 3-term window applied (1.7 Hz bin width).
- 87.5% overlap of transform blocks.
- 1 second of data analyzed and displayed per spectrum displayed.
- Typically, 9.45 seconds of data were displayed in a waterfall plot showing frequencies 5 to 250 Hz.

The results concerning infrasonic and other low-frequency components of bowhead calls are given under "PHYSICAL ACOUSTICS RESULTS--Bowhead Calls" (p. 91).

Aerial Reconnaissance and Surveys

General Approach

Aerial reconnaissance and surveys were a necessary component of the work required to meet specific objective 3, "To measure the short-term behavioral responses of ... whales ... to underwater playbacks...". Aircraft-based work was also important in addressing specific objective 6, "To document, as opportunities allow, other aspects of the movements, behavior, basic biology, disturbance responses and acoustic environment...".

Aerial surveys were necessary to find the best location for the projector site each day and to determine the number and spatial distribution of whales moving east near the projector site. Because the projector had to be established on the pack ice, it was not prudent to leave the ice-based crew on the ice overnight. The first priority each day was to find a suitable location on the pack ice for the sound projector. Ideally, this location would have been a large multi-year ice pan along an open E-W lead through which bowheads and white whales were migrating.

Each day when conditions were suitable for flying, a reconnaissance survey of the study area was conducted to document ice conditions, including the locations and orientations of leads, and to determine the distribution, numbers, general activities and directions of movement of whales. The flight route depended on ice conditions. In general, a series of widely-spaced transects was flown initially to determine the overall ice conditions and the locations and orientations of leads. A location for the sound projector was then selected. While the projector was being set up, additional surveys were conducted as far as 20 km west and southwest of the projector site. These additional surveys followed any prominent leads that whales might follow toward the projector site.

The need to avoid disturbing whales near Barrow necessitated setting up the projector ≥28 km east of the northeasternmost whaling camp (see specific objective 7, p. 6, and "STUDY AREA--Specific Study Location", p. 14).

Survey Methods and Data Recording

Aerial surveys were conducted from 29 April to 26 May 1990 in a DHC-6-300 Twin Otter aircraft. The Twin Otter is a high-wing aircraft powered by two turboprop engines. The aircraft was equipped with a GNS 500A Very Low Frequency navigation system, a radar altimeter, an inverter for 120 V/60 Hz power, three bubble windows (right center, left center, left rear), and an intercom system for communication among the four observers and two pilots. An aircraft with a ventral camera port was not available in 1990, so no photogrammetry work was possible. Also, the aircraft did not have a long-range fuel tank, so flights were limited to a maximum of about 4.5 h.

The aircraft was flown at ~200 km/h airspeed and, when possible, at 460 m (1500 ft) above sea level (ASL). When ceilings were lower than 460 m, the maximum possible altitude below the cloud layer was maintained. During the mid-day periods when a NMFS-National Marine Mammal Lab crew was conducting low-altitude photogrammetric work with another Twin Otter in the same region, we normally either flew at 460 m altitude or stayed on the ground. This avoided some aircraft safety concerns, and fulfilled a condition of the research permit issued by NMFS for this project (see specific objective 7, p. 6).

Four observers were present during almost all surveys. During surveys, they recorded observations onto audio cassette recorders. During surveys, one observer (right front) was in the co-pilot's seat, two were at bubble windows on the left and right sides of the aircraft two rows behind the pilot's seat, and the fourth was at a rear-left window. For each whale sighting, observers recorded the time, location, number, species, general activity, orientation, and ice conditions. Ice conditions were noted throughout the survey, particularly whenever a change in ice type or percent cover occurred. Aircraft position was recorded manually from the GNS whenever sightings were made and whenever the aircraft changed course.

When a whale was sighted, the observer notified other members of the crew over the intercom. Most bowhead whales were circled at least briefly to obtain information on the activity of the whale and to determine whether additional whales were present nearby. White whales usually were not circled, but large groups of white whales were circled to obtain more accurate counts and heading information.

No standardized surveys were conducted by helicopter. However, locations and headings of bowheads seen from the project's Bell 212 helicopter during ferry flights were noted.

Behavioral Observations

Aerial Observations

On 29 occasions in late April and May 1990, the aerial observation procedures of Richardson et al. (1985a,b, 1990a) were used to observe the behavior of bowhead or white whales, as required to meet specific objectives 3 and 5 (p. 6). Four observers in the Twin Otter aircraft circled high above the whales. In 1990, the aircraft always circled at 460 m ASL, which is high enough to avoid significant aircraft disturbance to bowheads, at least during summer and autumn. (Results from this study in 1989-90 suggest that sensitivity to the observation aircraft was no greater during spring than during previous summer and autumn work--see p. 264 and 282.) Airspeed during circling was ~165 km/h. The 29 behavioral observation sessions in 1990 ranged from 0.5 h to 3.5 h in duration, and totalled 46.8 h. For some analyses, we combined these data with those from the 17 observation sessions in 1989, which ranged from 0.1 to 3.3 h in duration and totalled 25.6 h (Richardson et al. 1990a).

The locations of the 29 observation sessions in 1990 are shown on Figure 5 (p. 42). Whenever possible, aerial observations were conducted near the ice camp in coordination with broadcasts of drilling platform sounds or associated control observations. Locations where coordinated ice-based plus aerial observations were obtained are shown in Figure 4 (p. 41).

Throughout each observation session, two observers on the right side of the aircraft dictated standardized behavioral observations via the intercom into a single tape recorder. These observers were in the co-pilot's seat and the seat two rows behind it. During each surface/dive sequence by bowheads, they described the same behavioral attributes as were recorded in our previous behavioral studies (Würsig et al. 1984, 1985; Richardson et al. 1985b, 1987b, 1990a; Koski and Johnson 1987).

The third observer, also on the right side during behavioral observations, operated an 8-mm video camera whenever whales were at the surface. Videotaping was through a flat window at the right-rear of the aircraft. A high-resolution (Hi8) camera was used, initially a Canon A1 Mk 1 with 8-80 mm lens and 1.4x teleconverter. From 21 May onward, a Sony CCD-V99 with 11-88 mm lens and 1.4x teleconverter was used. The video camera was usually operated with manual focusing and 1/1000 s shutter speed to provide sharp images when viewed in stop-frame mode. The time was displayed on each video frame. The behavioral dictation on the intercom was recorded onto the audio channel of the video tape recorder. The Hi8 cameras, used for the first time in 1990, provided greatly enhanced resolution over the Beta and standard 8-mm systems that we have used previously for this purpose.

In 1990, we resumed using a fourth observer on the observation aircraft, after using only three observers in 1989. The fourth observer surveyed for bowheads during reconnaissance periods, operated the sonobuoy receiving and recording system (see "PHYSICAL ACOUSTICS METHODS--Ambient Noise", p. 20), and assisted with behavioral observations when not busy with the sonobuoy system. The addition of this observer in 1990 proved to be very beneficial. In 1990, it was common for several bowheads to be simultaneously at the surface within the observation circle. The presence of the third observer allowed us to collect simultaneous and detailed data on more whales than could have been documented in his absence. It also avoided the necessity for the third observer to interrupt videotaping and project coordination activities to operate the sonobuoy system. This resulted in more complete videotape and sonobuoy records than would have been possible otherwise.

Behavioral data were transcribed from audiotape between flights, and the videotape was examined then or after the field season for details not noted during the real-time behavioral dictation. The combined data were coded numerically as in our previous work (see Richardson and Finley 1989:25-28 for details). These records were hand checked, and then typed into an

IBM-compatible microcomputer for computerized validation and analysis. Statistical analyses of the resulting behavioral data were done with the BMDP program system, version PC-90.

The numbers of bowhead surfacings and dives for which we have at least partial behavioral data are as follows:

	1989		1990	
	Surfacings	Dives	Surfacings	Dives
Presumably undisturbed whales	258	157	556	373
Potentially disturbed whales*				
Drilling noise playbacks	127	104	287	149
Aircraft at <460 m ASL	56	32	5	4
Sonobuoy drop	4	4	0	0
Other or combination	34	32	9	2
Subtotal	221	172	301	155
Total, undisturbed + disturbed	479	329	857	528

* Includes observations during 30-min or 15-min "post-disturbance" periods.

Ice-based Observations

Observations of bowheads and white whales were obtained by ice-based observers to help meet specific objectives 3, 5 and 6 (p. 6). When no whales were present, ringed and bearded seals were observed opportunistically. Upon arrival at the daily observation site, the theodolite was set up on the highest ice perch within ~300 m of the projector and ~20 m of open water. The observation site was usually on an ice ridge 2-5 m ASL. Two observers used binoculars to scan waters within ~2 km. When whales were sighted, one observer used a land surveyor's theodolite to track whales and observe their behavior. Observations were dictated to the second observer, who recorded all relevant data onto data sheets, into a field notebook, or into a cassette recorder.

A digital theodolite was used to measure successive positions of whales and seals in relation to the sound projector. In 1990 we used a Lietz/Sokkisha Model DT5A with 10 second precision. The height of the theodolite above sea level was determined each day by taking a gravity-referenced horizontal reading from a vertical stadia rod at the projector location. Theodolite bearings were measured in degrees, minutes and seconds from the horizontal zero (usually referenced to magnetic north) and a vertical zero referenced to gravity. Most ice ridges on which the theodolite was placed were less stable than desired. To control for error, the horizontal and vertical zeros were checked every 30 min (approx.) and after tracking episodes, and were reset if off by greater than one minute of arc.

The distances of whales from the theodolite were calculated initially by simple trigonometry, without correction for the curvature of the earth. This error is small for the combinations of perch heights and short (<2 km) distances involved in most of the 1990 observations of whales (Table 1). A whale 500 m from observers at a height of 2 m ASL would be only 5 m farther away than the distance calculated by the simple formula. However, for the small number of observations where the error associated with earth curvature would otherwise have been >5%, the distances were corrected by using a computer program that applied an iterative formula modified by E. Carlson from J.I. Wolitzky *in* Würsig (1978).

Table 1. Underestimation of distances calculated from theodolite data when curvature of earth corrections are not used.*

Theodolite Height	Distance from Theodolite				
	100 m	500 m	1000 m	1500 m	2000 m
1 m	0 m	10 m	96 m	433 m	N/A
2	0	5	41	163	490 m
3	0	3	27	98	273
4	0	3	21	73	191
5	0	2	17	56	143

* Formula modified by E. Carlson from J.I. Wolitzky *in* Würsig (1978)

Another potential error results from the refraction caused by temperature gradients in the air above the water (Sonntag and Ellison 1987). This error could be significant for low perch heights and whales more than ~1 km away when wind conditions are calm and air temperatures are low. The lack of reliable data on vertical temperature gradients in the air over leads prevents an evaluation of refraction error.

After the theodolite was set up, the relative locations of the projector, the manually-deployed sonobuoy, and the ice edge across the lead were documented by theodolite readings. These readings were repeated at ~2 h intervals to document shifts in ice configuration. Depending upon the width of the lead and the height of the perch, the waters within ~2 km of the theodolite were scanned intermittently with binoculars. When an animal was sighted, its bearing and depression angle were determined using the theodolite. Theodolite readings were recorded when the crosshairs were aligned with the waterline of the surfacing animal. An attempt was made to obtain a reading each time an animal surfaced for a blow. At each of these points, the time was also noted. Animals were tracked until they were no longer in view.

Additional notes were made in real time of initial and final sightings of all animals, including estimated distance and magnetic bearing from the projector, group size and composition, general behavior, direction of movement and subsequent shifts in direction, blow times, sighting conditions, presence of other species, and any other occurrences of interest, including aircraft flying overhead. These notes were made whether or not the theodolite and/or projector were in operation.

Playback Experiments

Playbacks were conducted to meet specific objective 3, "To measure the short-term behavioral responses of ... whales ... to underwater playbacks of the continuous drilling platform sound...". Drilling platform sounds were projected from a mobile ice-based camp that was established on the pack ice each day when weather and ice conditions were suitable. During one playback day in 1990 (9 May), observations of whales were obtained only from the ice camp because low cloud cover prevented aerial observations from altitude ≥460 m. During five days of playbacks (10, 11, 13, 16 and 21 May 1990), observations of whales were obtained by both the ice-based and aircraft-based crews. Bowheads were observed within 2 km of the operating sound projector during all six of these days. White whales were observed within 2 km during only one day in 1990--21 May.

In 1990, we made a greater effort than in 1989 to photograph the ice conditions around each projector site. Such photographs are needed to prepare maps of whale movements past the projector. At least once and usually twice during each day with coordinated aerial and ice-based work, the aircraft climbed to an altitude of 3000-5000 ft (cloud ceiling permitting). Oblique and near-vertical photographs of the area were taken from several angles using 35-mm cameras with 35-mm wide angle and 17-mm very wide angle lenses. Some examples appear as Plates later in this report. In addition, Polaroid photographs of the ice and leads were taken at the same times to provide prints onto which notes could be made immediately.

Playback Equipment and Procedures

Each day when weather and ice conditions permitted, the ice camp was established on the pack ice along a lead. When possible, the camp was placed to the east or northeast of whales located by aerial reconnaissance. The sound projector and ancillary equipment, the sound recording and monitoring equipment, and the theodolite were set up. This process normally required 1-2 hours after arrival at the site. The theodolite crew then watched for approaching whales, supported by the aerial crew whenever feasible. If no whales were seen close to the projector, it was started. To avoid startle reactions, we did not intentionally start the projector when bowheads were within 1 km. From 13 May onward, the sound level was increased gradually over 1 min (13 May) or 5 min (16, 21 May).

A single broadband J-11 projector was used for all playback experiments. The J-11 can produce a source level for *Karluk* of about 167 dB re 1 μPa-m without distortion. Its effective bandwidth is rated as 20-12,000 Hz, but its output is greatly reduced below 63 Hz and slightly reduced between 63 and 80 Hz (see "PHYSICAL ACOUSTICS RESULTS--Fidelity of Playbacks", p. 88). The J-11 was powered by a 250 W Bogen MT250 power amplifier. The J-11 and its ancillary equipment were portable by helicopter, which allowed us to conduct "single-day" experiments at changing locations.

To operate the amplifier and other electronic equipment for a significant length of time, it was necessary to use a generator instead of batteries. In 1990, the generator was operated during most control periods as well as during playbacks to ensure that control and playback periods differed only by the emission of sound from the projector during playbacks. The 2.2 kW gasoline-powered Honda generator produced significant airborne noise. Little of this noise was transmitted into the water because of attenuation by the snow-covered ice. Underwater sound from the generator would not have been detectable by whales during playback experiments, but might have been detected by whales close to the ice camp during control periods while the generator was operating (see p. 98, "PHYSICAL ACOUSTICS RESULTS--Generator Noise"; p. 244, "BOWHEAD RESULTS--Non-playback Effects of Ice Camp"; and, for 1989 data, Richardson et al. 1990a:97).

It was important to obtain the most accurate possible data on the relative positions of whales and the sound projector. These data were needed to plot whale movements and to estimate received sound levels when these were not measured directly by sonobuoys. When whales were within ~1 km of ice-based observers and within their field of view, the most precise positional data were obtained with the theodolite. However, for whales observed from the air, other procedures were necessary.

The absolute location of the ice camp was determined using the VLF navigation systems on the Twin Otter and helicopter (usually accurate within about 1 km in 1990) and using a Si-Tex model A-310 satellite navigation receiver at the ice camp (accuracy 0.1-0.2 km). The position of the ice camp often changed substantially during an experiment due to wind- and current-induced drifting of the ice. To account for this, all whale sightings and movements were plotted relative to the sound projector. To help determine whale positions relative to the ice camp, the observation aircraft was often flown from the location where whales had just dived to the ice camp. By flying directly over these two positions within a short interval, the aircraft's VLF navigation system provided accurate (±0.3 km) data on the whale-to-projector distance and bearing even though absolute position readouts from the VLF system were less precise. In addition, during playbacks we frequently recorded the position of the whale according to the aircraft's VLF navigation system, and we made visual estimates of the distance from the whale to the projector during most whale surfacings. Whale-to-projector bearings were estimated by reference to the aircraft's gyrocompass. Upon our return to the Barrow airport after each flight, we recorded the amount of drift in the absolute GNS readout during the flight. In 1990 it was usually 1 km or less.

Acoustical Monitoring

Sound levels reaching whales during playback experiments were measured and/or estimated using several techniques, as described under "Measured Sound Levels During Playbacks" and "Sound Levels Received..." (p. 23-25). By having a variety of monitoring capabilities, we were able to obtain the necessary data on sound exposure levels in a wide variety of field situations, including situations where some methods were impractical. The transmission loss measurements from 1989 and 1990, along with mathematical models of transmission loss, provided estimates of received level at places and times where direct measurements of sounds reaching whales were not available.

Behavioral Observations

To maximize the power of the observations in assessing the hypotheses, we planned to use whales approaching the sound projector as their own controls. Our intent was to compare the behavior of the same whales when they were at various distances from the projector. This approach reduces the complications caused by differences in the natural activities of different individual whales. We planned to begin observing the movements and behavior of whales when they were far enough from the projector that they could not hear it or, at the least, were not likely to react to it.[5] We then intended to observe their movements and behavior as they approached and passed the projector.

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[5] Previous studies of bowheads and other baleen whales have shown that they generally show no discernible reaction to steady sounds that are weak but presumably detectable (Richardson et al. 1991).

Because the projector had to be reestablished on the ice each day, the projector often began operating while whales were already under observation from the aircraft. To eliminate observer expectancy biases, we prevented the two primary behavioral observers in the aircraft from knowing whether the sound projector was operating. This "blind" observation protocol for the primary observers was fully achieved in 1990. The third observer on the aircraft (project director) was in radio communication with the acoustician on the ice, and was aware of projector status. The fourth observer on the aircraft was usually aware of projector status because he was monitoring the signals received by sonobuoys, which detected the projected drilling sound when it was present. The 3rd and 4th observers did not discuss projector status with the primary behavioral observers until after the behavioral data had been transcribed from audiotape onto dataforms by those primary observers.

In addition, the ice-based crew recorded whale behavior and movements with the aid of the theodolite during playback experiments. Because of the low vantage point from the ice, ice-based observers could not see whales unless they were within ½-2 km of the projector (depending on ice conditions). The most valuable data obtained from the ice-based observations were data on the closest point of approach to the projector and on the tracks of whales that approached or passed the projector. More precise data of these types could be obtained by theodolite than by aerial observations. Also, ice-based observers sometimes were able to collect data when aerial observations were impractical because of low cloud ceiling (9 May 1990) or limited aircraft endurance.

Because of their proximity to the projector site and their involvement in its deployment and retrieval, the ice-based observers sometimes were aware of projector status (on or off). However, most of their data were theodolite readouts, which do not involve subjective judgments. Thus, observer bias would not be a problem in these data. Furthermore, the ice-based biologists often were unaware of projector status. The generator was operated during both playback and control periods. During control periods as well as playbacks, the tape recorder used to play back the *Karluk* sounds was operated, and the *Karluk* sounds were played over a monitor speaker in the tent at the ice camp. With this procedure, only the acoustician at the camp knew whether *Karluk* sounds were also being projected into the water.

To determine the reactions of whales to the drilling sounds, we planned to conduct three types of comparisons of whale movements and behavior: *(1)* For whales that approach and pass the operating projector, examine movements and behavior as a function of distance from the projector, allowing each animal or group to serve as its own control. *(2)* Compare the movements and behavior of whales passing the ice-based crew at times when the projector is operating vs. silent. *(3)* Compare the movements and behavior of whales seen near the operating projector vs. those seen at times and locations when the ice-based crew is absent.

In 1989, because there were few opportunities for playbacks, we decided to operate the projector on each day when whales were passing it. Thus, few data of the type needed for comparison (2) were obtained in 1989. In 1990, control observations with the ice camp present were obtained during parts of most days with playbacks, and on two days when there were no playbacks (29 April and 19 May). Thus, all three types of control data were obtained in 1990.

GENERAL CHRONOLOGY OF 1990 FIELD ACTIVITIES

Daily Chronology, 1990

The ice-based crew arrived at Barrow on the evening of 25 April and organized and tested the sound projection and recording equipment on 26 April. On 27 April a transmission loss experiment was attempted but slush ice and technical difficulties caused the test to be aborted (Table 2). The aerial observation crew set up and tested their data recording equipment before the Twin Otter aircraft arrived.

On 28 April a storm warning was issued for the Barrow area. The Twin Otter arrived at Barrow and the aircraft-based crew installed their electronic equipment in the Twin Otter.

The Twin Otter crew conducted a reconnaissance of the area ENE and NE of Barrow on 29 April. They found a nearshore lead that was several kilometers long and oriented WNW to ESE along the landfast ice edge ENE of Barrow. Several bowheads were found moving along a mostly refrozen secondary lead extending ENE from the main nearshore lead. The first behavior observation session of the year was conducted on 6 scattered bowheads in the secondary lead (Table 3). The ice-based crew set up the ice camp beside a small opening along the northern side of the secondary lead (Fig. 4). However, the projector remained quiet during this day (control observations). The Twin Otter crew conducted a second behavior observation session near and to the WSW of the ice camp (location B2 *in* Fig. 5).

The Twin Otter crew conducted surveys ENE of Barrow on each day from 30 April to 4 May and found little open water and no bowheads. In the absence of whales, the ice-based crew conducted transmission loss tests on 1 and 2 May. Then, on 4 May, they projected *Karluk* drilling platform sounds into the water along a small refrozen lead amidst the pack ice, in the hope that whales might approach (Table 2, Fig. 4). However, no whales were seen near the camp.

On 5 May the Twin Otter crew found a single bowhead traveling along a long thin lead in the pack ice and followed this whale for over an hour (B3 *in* Fig. 5). The ice-based crew set up along this lead during this time, but no additional bowheads were seen. A combination of fog and high winds prevented any useful work on 6-8 May (Table 2).

On 9 May the Twin Otter crew conducted a survey during conditions of low ceilings; they found 12 scattered bowheads and directed the ice-based crew to the north side of the main nearshore lead where several bowheads had been sighted (Fig. 4). The ice-based crew obtained ~27 observations of bowheads passing when the projector was quiet and when *Karluk* sounds were being projected. Aerial observations were not possible during this playback experiment because the cloud ceiling was <460 m near the projector. However, migrating whales were observed farther west where the sky was clear (B4, B5 *in* Fig. 5).

On 10 May many bowheads were sighted moving across the main lead and entering a secondary lead along the north side of the main lead. The ice-based crew set up along the secondary lead, and observed bowheads moving past the sound projector both during playback and control periods. Because of variable cloud conditions and ceilings at different locations and

Table 2. Summary of daily activities and weather and ice conditions, 27 April-25 May 1990.

	Ice-based Crew								Aircraft-based Crew			
Date	Ferry Flights	Transm. Loss Test	*Karluk* Projections	Number of Bowheads	Location	Other	Overall Ice Conditions	Cloud Ceiling/ Visibility	Survey (h)	Behavior Obs. Sess. (h)	Location	Other
27 Apr	2			0	71°30' 155°38'	Ice reconnaissance. Attempted TL test but faulty equipment.	99% Small to medium-sized openings, but no leads.	Clear or high cloud.				
28 Apr	0					Equipment maintenance.	99%	Poor weather was forecast.				Aircraft arrives at Barrow.
29 Apr	2			2	71°32' 154°59'	Control obs. No projections.	97% Lead along landfast ice NE of Barrow.	Clear	3.4	3.3	71°31' 155°03'	Obs. of presumably undisturbed behavior.
30 Apr	3			0	71°31' 154°44'	Refrozen lead. TL test but faulty equipment.	97% New ice formed overnight.	Clear	1.8		Survey ENE of Barrow.	
1 May	1	#1		(1)*	71°37' 156°09'	One bowhead sighted near a TL station. Bowheads also heard.	97%	Hazy with low cloud. Poor vis.	1.7		Survey ENE of Barrow.	
2 May	2	#2		0	71°34' 155°02		97%	Ceiling 150-450 m. Variable vis.	1.5		Survey ENE of Barrow.	
3 May	0					Equipment maintenance.	97%	Ceiling 180-300 m.	2.6		Survey ENE of Barrow.	
4 May	4		P1	0	71°36' 155°49'	*Karluk* playback; bowheads heard but not seen. Broadcast into E end of minor refrozen lead.	97%	Fog in mid AM, then clear. Some fog in SE part of study area in PM.	3.5		Survey ENE of Barrow.	
5 May	2		P2	0	71°35' 155°27'	*Karluk* broadcast into narrow, refrozen lead.	95% New cracks forming.	Light fog in AM. Low cloud in PM.	2.7	1.7	71°36' 155°30'	Obs. of presumably undisturbed behavior.
6 May	1			0		Flight aborted due to fog. Analyzed TL data.	95% Lead W of Barrow ≈300 m wide.	Fog.	0.4		Survey ENE of Barrow.	
7 May	0					Analyzed data.	95%	Fog.				Poor weather, no flying.
8 May	0					Analyzed data.	95%	Fog.				Poor weather, no flying.

Continued...

Table 2. Continued.

	Ice-based Crew								Aircraft-based Crew			
Date	Ferry Flights	Transm. Loss Test	*Karluk* Projections	Number of Bowheads	Location	Other	Overall Ice Conditions	Cloud Ceiling/ Visibility	Survey (h)	Behavior Obs. Sess. (h)	Location	Other
9 May	2		P3	27	71°36' 155°29'	*Karluk* broadcast along N side of narrow lead amidst pack ice.	90%	Fog.	2.7	2.3	71°31' 156°02'; 71°30' 156°08'	Obs. of presumably undisturbed behavior. Sonobuoy disturbance.
10 May	2		P4	30	71°35' 155°16'	*Karluk* broadcast along E side of large open lead.	85% 5-10% ice in 4 km-wide lead ENE of Barrow.	Fog in AM. Some fog and low cloud in PM.	1.8	5.5	71°33' 155°24' 71°36' 155°17'	Obs. of presumably undisturbed behavior. *Karluk* projection experiment with pre- and post-plbk control obs.
11 May	2		P5	12	71°35' 155°29'	*Karluk* broadcast along NW side of large open lead.	85% 0-50% pans in lead along landfast ice.	High overcast, patchy fog. Good vis.	2.5	5.1	71°31' 155°40' 71°33' 155°30'	*Karluk* projection experiment with pre-plbk control obs. Post-plbk control obs. followed by helicopter overflight experiment.
12 May	1			0		Flight aborted due to fog. Analyzed data.	85%	Fog until mid PM, then high overcast and good vis.	1.1	3.1	71°31' 155°23'	Obs. of presumably undisturbed behavior.
13 May	2		P6, P7	138	71°26' 154°47'	*Karluk* broadcast along N side of a narrow primary lead.	95%	High overcast and good vis. in AM. Occas. low cloud in PM.	4.0	5.7	71°26' 154°47'	Distorted *Karluk* and normal *Karluk* projection experiments with post-plbk control obs.
14 May	0						95%	Fog.				Poor weather, no flying.
15 May	0						90%	Fog.				Poor weather, no flying.
16 May	2		P8	54	71°26' 154°08'	*Karluk* broadcast along S side of open lead amidst pack ice.	90%	Fog until mid AM, then good weather.	4.4	3.8	71°26' 154°12'; 71°27' 154°08'	*Karluk* projection experiment with pre- and post-plbk control obs.
17 May	1			0		Flight aborted due to fog. Analyzed data.	90%	High cloud and strong winds, then rain.	1.8			
18 May	0						90%	Fog.				Poor weather, no flying.
19 May	2			1	71°34' 155°09'	Control obs. No projections.	90%	Ceiling 100-180 m, then clearing.	2.3		Survey ENE of Barrow.	

Continued...

Table 2. Concluded.

	Ice-based Crew								Aircraft-based Crew			
Date	Ferry Flights	Transm. Loss Test	*Karluk* Projections	Number of Bowheads	Location	Other	Overall Ice Conditions	Cloud Ceiling/ Visibility	Survey (h)	Behavior Obs. Sess. (h)	Location	Other
20 May	0						85%	Ceiling and vis. marginal all day. Snowshowers in AM and winds to 55 km/h in PM.				Poor weather, no flying.
21 May	2			0	71°35' 155°31'	Control obs. No projections.	85% Wide lead E to 155°50', then very narrow.	Clear. Winds 20 to 25 kt.	2.3	5.5	71°34' 155°48'; 71°36' 155°43'; 71°37' 155°49'	Obs. of presumably undisturbed behavior. *Karluk* projection experiment with pre-plbk obs.
			P9	2	71°36' 155°48'	*Karluk* broadcast into hole amidst pack ice at second ice camp location.						
22 May	0						80%	Poor weather all day.	0.5		Survey ENE of Barrow.	
23 May	0						80%	Fog and snow in AM. Extensive fog bank across most of study area.	2.0	2.0	71°44' 156°36'; 71°35' 156°14'	Obs. of presumably undisturbed behavior. Boat (outboard) disturbance at end of session.
24 May	2	#3		(3+)	71°36' 154°57'	Bowhead and white whales heard at various TL stations.	80% Main lead reduced to ≤1 km wide from W of Barrow to 155°45'.	High cloud, good visibility except for continuous fog in E part of study area.	4.0	3.5	72°04' 155°13'	Obs. of presumably undisturbed behavior.
25 May	1	#4		0	71°34' 155°26'		80% Major secondary leads present ENE of Barrow.	High cloud. Good visibility.	2.9	5.0	71°58' 155°24'; 72°06' 154°58'	Obs. of presumably undisturbed behavior.
26 May	0						80%	High, thin cloud. Much fog offshore to N and E.	2.4		Survey ENE of Barrow.	Obs. of presumably undisturbed behavior.

* Numbers in parentheses indicate whales observed during ferry flights or TL tests.

Table 3. Summary of aerial behavioral observation sessions, 1990.

Date 1990	Behavior Obs. Sess.	Location	Obs. Period	No. of Bowheads		General Activity	Predominant Orientation °T	Predominant Speed of Travel	Size Classes	Disturbance	Water Depth (m)	Sea State	% Ice	
				circle	area								in circle	overall
29 Apr	1	71°31′ 155°04′	11:39- 12:49	4	6	feeding/ social/ travel	various	slow	mother yearling & unknown	none	18	1	85	97
29 Apr	2	71°31′ 155°01′	14:42- 17:21	2	5	travel	080-100	slow	adult & unknown	none	18	0	80	97
5 May	3	71°35.5′ 155°30′	12:17- 14:00	1	1	travel	various	medium	unknown	none	165	1	90	95
9 May	4	71°30.5′ 156°02′	21:14- 22:21	3	7	travel	various	medium	1 adult subadult & unknown	none to 22:00:56; then sonobuoy drop	28	2	<<1	90
9 May	5	71°29.7′ 156°08′	22:23- 23:34	7	9+	travel	070-090	medium	unknown	none	20	2	<<1	90
10 May	6	71°33.2′ 155°23.5′	13:39- 14:43	4	9+	mainly social & sexual/ small amt. travel	various	various	adult subadult & unknown	none	48	1	5	85
10 May	7	71°35.5′ 155°15′	14:48- 15:36	≈3-4	≈8-10	travel	various	medium	subadult & unknown	none to 15:32:09; then *Karluk* plbk	66	1	10	85
10 May	8	71°35.5′ 155°18′	15:42- 16:29	3	6	social/ travel	various	medium	subadult adult & unknown	*Karluk* plbk throughout	86	1	5	85
10 May	9	71°35.7′ 155°19′	18:06// 21:02 (2.80 hr)	10	25	social/ travel/ resting/ breach	various	various	unknown	*Karluk* plbk until 20:50:30; then post-plbk	91	0-1	5	85

Table 3. Continued.

Date 1990	Behavior Obs. Sess.	Location	Obs. Period	No. of Bowheads		General Activity	Predominant Orientation °T	Predominant Speed of Travel	Size Classes	Disturbance	Water Depth (m)	Sea State	% Ice	
				circle	area								in circle	overall
11 May	10	71°31.5' 155°38'	11:45-13:04	6-7	8	travel/ occ. social	various	medium	adult & unknown	none	21 (later)	0-1 <1-5	2;	85
11 May	11	71°31.4' 155°43'	13:48-14:45	1	± 5	travel	050	medium	unknown	none	19	0	25 (0-SE; 50-NW)	85
11 May	12	71°32.6' 155°30'	15:55-17:26	5	8	travel/ some social	060-080	medium	adult subadult & unknown	none to 16:27:29; *Karluk* plbk 16:27:30-17:48:15	20	1	2 (0-5)	85
11 May	13	71°32.8' 155°30'	17:54-19:14	2	3	travel/ some rest, social	various	medium	unknown	none to 18:56:23; then helic. overflight	22	1	5 (1-15)	85
12 May	14	71°31.2' 155°22.6'	16:10-19:14	3	6	travel/ some feeding	060-090	medium	2 adults & unknown	none	20	1	5 (0-15)	85
13 May	15	71°26.1' 154°47.4'	12:47-15:23	5	9	travel	various	medium	4 adults & unknown	none to 13:00:39; then *Karluk* plbk (distorted)	27	1	88	95
13 May	16	71°26.1' 154°47.3'	16:41-18:41	6	18	travel/ some social	110-140	slow-medium	1 subadult 5 adults & unknown	*Karluk* plbk throughout	27	1	88	95
13 May	17	71°26.1' 154°47.3'	18:43-19:47	3	8	travel/ occ. social	120	slow-medium	subadult 2 adults & unknown	*Karluk* plbk until 18:46; post-plbk 18:46-19:16	27	1	88	95
16 May	18	71°26' 154°12'	12:28-12:58	6	12	travel/ social	100-110	slow-medium	2 adults 1 subadult & unknown	none	29	1-2	60	90

Continued...

Table 3. Concluded.

Date 1990	Behavior Obs. Sess.	Location	Obs. Period	No. of Bowheads		General Activity	Predominant Orientation °T	Predominant Speed of Travel	Size Classes	Disturbance	Water Depth (m)	Sea State	% Ice	
				circle	area								in circle	overall
16 May	19	71°26.5′ 154°07′	13:26-15:19	3-8	15-18	travel/ very small amt. social	100	medium	adult	pre-plbk; *Karluk* plbk begins 14:10:16	40	1-2	40	90
16 May	20	71°27′ 154°08′	17:38-19:05	5	6	feeding/ some travel/ breach	various	none-medium	adult subadult & unknown	*Karluk* plbk until 17:50:00; post-plbk 17:50-18:20	40	1	80	90
21 May	21	71°35′ 155°45′	8:48// 11:24 (2.10 hr)	(a) 2 (b) 2 (c) 2	(a) 10 (b) 10 (c) 5	travel	various	medium	2 calves 2 mothers subadult & unknown	none	(a) 150 (b) 205 (c) 205	(a) 3 (b) 3 (c) 3	(a) 5 (b) 60 (c) 60	85
21 May	22	71°36′ 155°48′	13:14-14:32	2	2	travel	030-060	medium	adult & unknown	*Karluk* plbk throughout	210	3	75	85
21 May	23	71°37′ 155°49′	14:35-16:41	2	4	travel	various	slow-medium	2 adults & unknown	*Karluk* plbk until 15:57:23; post-plbk to 16:27	220	3	75	85
23 May	24	71°44′ 154°36′	09:11-10:12	1	1	unknown	various	slow	unknown	none	82	1	50	80
23 May	25	71°35′ 156°14′	18:30-19:28	2	4	travel/ riding	060-090	medium	1 calf 1 mother	none to 19:25; then whaling boat	160	1	5	80
24 May	26	72°04′ 155°13′	18:31-22:00	2	2	travel	various	more slow than medium	1 calf 1 mother	none	330	1	80	80
25 May	27	71°57′ 155°23′	11:06-13:00	2	4	rest/feed	various	slow	2 calves 2 mothers	none	285	2	85	80
25 May	28	71°59′ 155°24′	15:05-15:38	2	2	rest	various	none-slow	1 calf 1 mother	none	230	1	85	80
25 May	29	72°06′ 154°58′	15:46-18:11	2	5	rest, aerial & unknown to 16:18; then travel	various	various	2 calves 2 mothers & unknown	none	475	0-1 2	90 until 17:10; 60 after 17:10	80

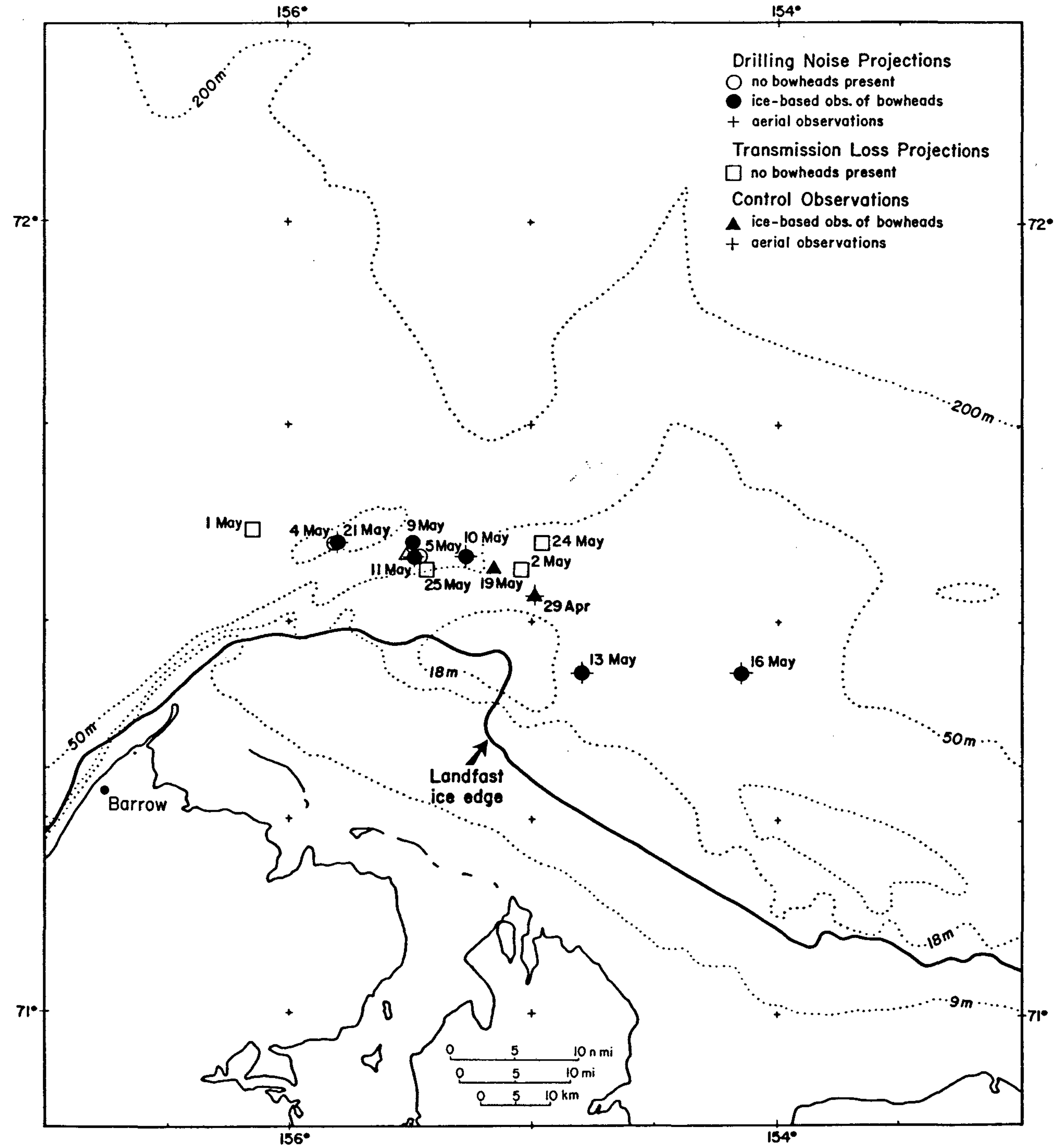

FIGURE 4. Locations where ice-based crews conducted transmission loss tests, broadcast drilling sounds, and made control observations, 29 April-25 May 1990. Solid symbols represent days when bowheads were observed. Locations are approximate because of ice drift during the course of each day's work.

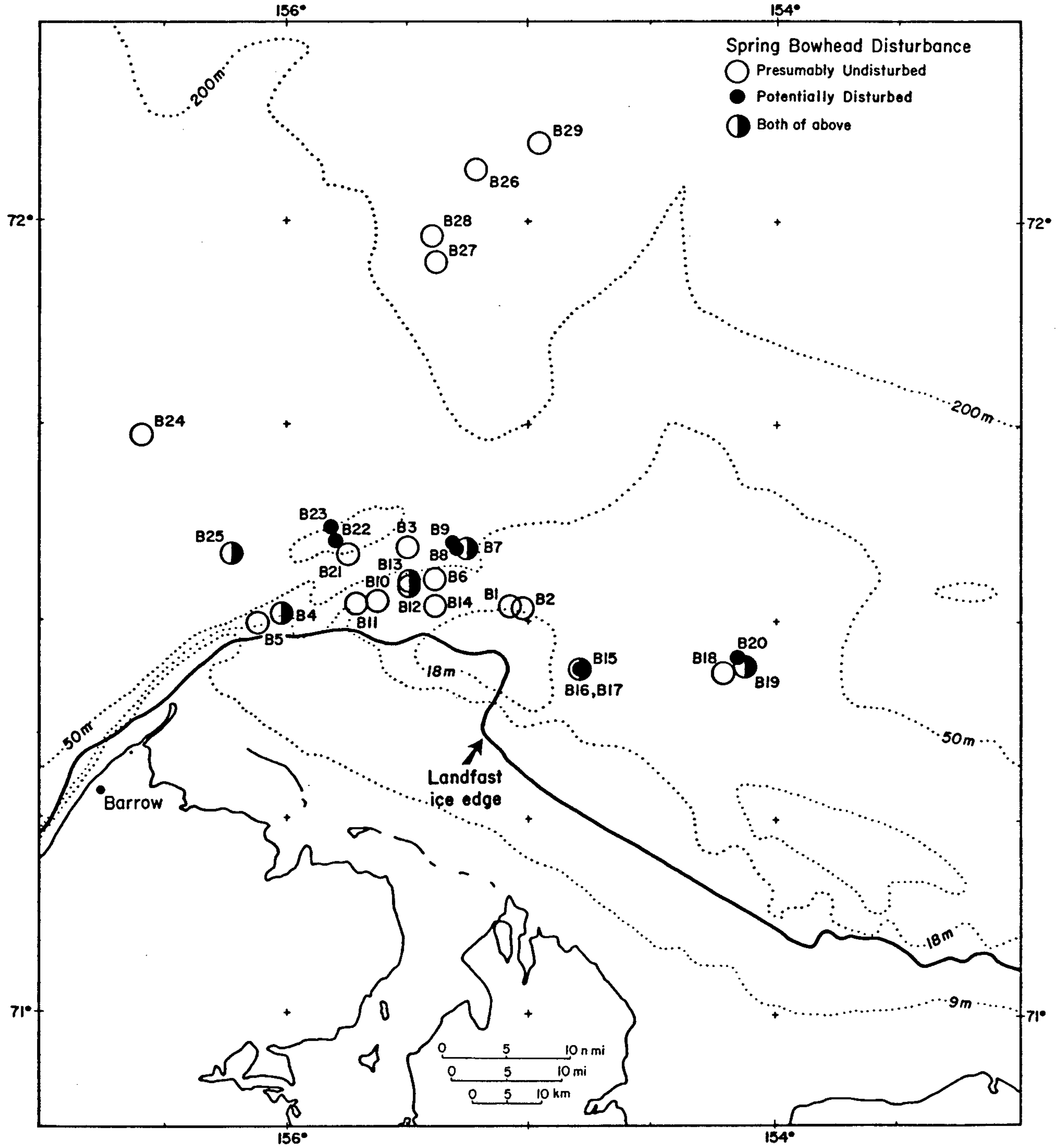

FIGURE 5. Locations where behavior of bowhead whales was observed by the aerial crew, 29 April-25 May 1990. Numbers (prefixed by a B) refer to behavior observation session numbers referenced in Table 3.

times, the Twin Otter crew obtained behavioral observations on whales both near and away from the ice camp location (Table 3; B6-B9 *in* Fig. 5).

On 11 May, the ice-based crew set up on the south side of an ice pan drifting near the north side of the main lead. Observations of bowheads were obtained when the projector was silent and when it was playing *Karluk* drilling sounds. However, few bowheads were seen near the ice camp; most whales were migrating past ~3 km farther south in the middle of the main nearshore lead. The Twin Otter crew conducted 4 observation sessions (B10-B13 *in* Fig. 5), but none of the whales that were followed passed closer than 2 km from the projector location under either quiet or playback conditions. Near the end of the day, a helicopter overflight experiment was done; the project's Bell 212 helicopter was directed to fly at 150 m altitude over bowheads that were being observed from the Twin Otter circling at 460 m altitude.

The ceilings were low for most of 12 May, but the Twin Otter crew flew in the late afternoon and obtained extensive control data on the migratory behavior of a group of whales traveling east in the main lead (B14 *in* Fig. 5).

On 13 May, the ice camp was established along a long thin lead that extended ESE from the eastern end of the main nearshore lead. Large numbers of migrating bowheads were observed by the ice-based and aerial crews when the projector was silent and when it was projecting *Karluk* drilling platform sounds (Table 2). For part of the day, the projected sounds were distorted because the projector was failing. Later in the day a replacement projector was used and normal drilling sounds were projected. The aircraft-based crew observed whales migrating past the projector during 3 observation sessions (Table 3). Some bowheads were followed from as far as 6 km west to 4 km east of the projector (B15-B17 *in* Fig. 5).

Low cloud and fog prevented flying on 14 and 15 May. The first Twin Otter flight on 16 May was unsuccessful due to fog; however, during the second flight, large numbers of whales were found moving east and NE through a secondary lead amidst the pack ice 100 km east of Barrow. The ice camp was set up on a pan toward the eastern end of this lead (Fig. 4) and observations were obtained of bowheads passing the projector before and during playbacks of drilling sounds. The aircraft-based crew followed bowheads as they approached and receded from the projector (Table 3; B18-B20 *in* Fig. 5).

A survey by the Twin Otter on 17 May found 5 bowheads and 150 white whales near the eastern end of the main lead and in the pack ice east of there; however, poor weather prevented behavioral studies. The poor weather conditions continued throughout 18 May. On 19 May ceilings were too low for aerial observations of behavior but visibility was good. The Twin Otter crew conducted a survey and directed the ice-base crew to an area of loose pack ice north of the main lead (Fig. 4) where they obtained limited control observations.

Poor weather and very strong winds prevented fieldwork on 20 May (Table 2). The weather improved on 21 May although the winds remained strong (40-45 km/h). The aerial crew found bowheads migrating through the main lead and entering a series of small openings in the pack ice north of the main lead. The ice-based crew was directed to this area, and a *Karluk* drilling noise playback was conducted (Fig. 4). Two bowheads and many white whales were observed from the ice camp, and several bowheads were followed from the Twin Otter

(Table 3; B21-B23 *in* Fig. 5). This was the only day in 1990 when we observed white whales near the operating projector.

Weather conditions were poor on 22 May and variable on 23 May. The Twin Otter crew was able to conduct two brief observation sessions on bowheads by finding whales in clear areas amidst the fog (B24-B25 *in* Fig. 5). On 24 May the ice-based crew conducted a third transmission loss test (Fig. 4) after the Twin Otter crew were unable to find bowheads. For 3.5 h in the late afternoon, the Twin Otter crew observed a mother-calf pair in the pack ice 103 km north of Barrow (B26 *in* Fig. 5).

The field season had been scheduled to end on 24 May. However, the budget situation allowed another 2 or 3 days of fieldwork, and there were still bowheads in the area. Hence, the season was extended for two more days.

On 25 May the ice-based crew conducted a fourth transmission loss test in the pack ice just north of the main lead (Fig. 4). The Twin Otter crew conducted three observation sessions on mother-calf pairs far north in the pack ice, near 72°N (Table 3; B27-B29 *in* Fig. 5). Aerial reconnaissance failed to locate whales closer to Barrow where disturbance tests could be conducted.

Two brief surveys were conducted on 26 May but low fog over much of the offshore area prevented any useful work.

Summary of 1990 Field Activities

The ice-based crew worked from the ice on 16 days between 27 April and 26 May in 1990. They conducted transmission loss tests on four days and projected *Karluk* drilling platform sounds into the water for several hours on each of 8 days. On 6 days, bowheads were observed in waters that were ensonified by the projector broadcasting drilling platform sounds. However, on one of these days (11 May) bowheads did not approach closer than 2 km from the operating projector. Whales were seen by the ice-based observers near the operating projector on 9, 10, 11 (2 km), 13, 16 and 21 May 1990. Bowheads were observed near the quiet projector on those six dates plus 29 April and 19 May.

The aircraft-based crew conducted reconnaissance surveys on 23 days from 29 April to 26 May, of which the surveys on 20 d were effective. The aerial crew conducted 29 behavior observation sessions on 12 days. The aerial crew observed bowheads near the operating projector on 10, 13, 16 and 21 May, and also followed whales within 3.5 km of the operating projector on 11 May.

Ice conditions and whale migration patterns in 1990 were similar to "normal" patterns, and there were several good opportunities to conduct tests of the reactions of migrating bowhead whales to projected industrial sounds. Far more data on the movements and behavior of bowheads near the operating projector were obtained in 1990 than in 1989. The improved success was attributable to the better ice conditions, better weather conditions (including frequent high ceilings), and the presence of many bowheads during some days when weather and ice conditions were suitable for aerial and ice-based work. However, fewer white whales were present in 1990 than in 1989, so the 1990 data on white whales provide only a limited supplement to the 1989 results.

The mobility of the projector site and of the behavioral observation platforms (ice camp and aircraft) was essential. Although large numbers of bowheads were seen migrating eastward during this study, no or very few data would have been collected in either year had the projector and observation platforms been restricted to the fast ice edge within our study area. In addition, the corridors followed by bowheads changed almost daily. No one location amidst the pack ice would have provided the quantity of biological data that we were able to collect during this study.