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ACOUSTIC EFFECTS OF OIL PRODUCTION ACTIVITIES ON BOWHEAD AND WHITE WHALES VISIBLE DURING SPRING MIGRATION NEAR PT. BARROW, ALASKA--1989 PHASE:

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

by

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PROJECT ORGANIZATION

This contract was conducted by LGL Ltd., environmental research associates, assisted by two subcontractors: Greeneridge Sciences Inc. and BBN Systems & Technologies Corp. **LGL** organized the project as a whole, and conducted the biological aspects of the work. B. Würsig and M. Smultea of the Marine Mammal Research Program, Texas A & M University, worked with LGL on the biological components. **Greeneridge** was responsible for the physical acoustics portions of the fieldwork and for much of the acoustical analysis. **BBN** provided specialized acoustical modeling expertise. The affiliations of the authors are as follows:

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ABSTRACT

Previous studies of the reactions of bowheads to noise from oil industry operations have all been conducted during late summer or autumn. Concern has arisen about potential reactions of bowheads and white whales to oil industry noise in leads through which whales migrate around northern Alaska in spring. Hence, MMS funded an experimental study to determine physical acoustic conditions, especially rates of sound attenuation, in spring lead systems; and the short-term behavioral responses of whales to sounds from production platforms, icebreakers, and aircraft. The work must be done without interfering with subsistence whaling or other research. After consultation with local groups and other scientists, a study area centered ~60 km ENE of Pt. Barrow was selected. During the first field season, in 1989, priority was given to testing whale reactions to continuous noise recorded near a drillrig on a grounded ice pad.

The primary field procedure was to use an underwater sound projector to broadcast recorded industrial noise into the water such that the reactions of approaching whales could be observed. The projector was also used to broadcast various test sounds in order to measure sound attenuation rates. Between 29 April and 30 May 1989, a helicopter-supported crew conducted sound transmission loss experiments on five days and aircraft noise measurements on two days. They also projected drilling noise into the water for several hours on each of 11 days. On five of these days, whales were observed within the ensonified area. An aerial-observation crew conducted reconnaissance surveys on 24 days from 1 to 30 May, behavioral observations of whales on 10 days, and bowhead photogrammetry on 8 days. Because of difficult ice conditions, all ice-based work had to be done from the pack ice rather than the landfast ice edge, and sample sizes for most types of biological observations were smaller than desired.

During playback experiments, low-frequency (<300 Hz) drilling noise was projected into the water at a source level of ~164 dB re 1 μPa. This noise was strong within ~1 km of the projector, and faintly detectable out to at least 4-5 km (occasionally to 9-10 km). Underwater sound attenuated more rapidly under pack ice conditions NE of Pt. Barrow in spring than found previously in open waters of the Beaufort Sea during late summer.

During playbacks of drilling sound, several bowheads migrated NE within 1 km of the projector, well within the ensonified area; one whale swam within 120 m. However, one mother/calf pair swam *west* away from the projector, possibly exhibiting avoidance. These limited data show that some bowheads tolerated low-frequency drilling noise without interrupting or diverting their migration; others may have reacted strongly. It would be premature to generalize these few data to the whole population, or to other types of industrial sounds.

White whales migrating toward the projector traveled toward it until they came within a few hundred meters. Some then continued past it without apparent hesitation or turning. Others definitely reacted at distances on the order of 200-400 m; they slowed, milled and in some cases reversed course temporarily. However, within a few minutes, they continued past the projector, sometimes passing <50-100 m from it. We saw no evidence that white whales reacted at distances >200-400 m. Again, it would be premature to generalize these observations to other situations or other types of noise.

Although additional data are required before definite conclusions can be reached, the 1989 work provided useful results on sound propagation and whale responses, and demonstrated that it is possible to conduct a study of this type despite the logistical and other difficulties involved.

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 1989 Objectives

Prior to the 1989 field program, it was decided that the study would include at least a second spring field season, in 1990. It was agreed that the highest priority during the initial 1989 field program 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. The basic field technique to be used for these tests consisted of underwater playbacks of recorded industrial sound. In 1989, all opportunities for playbacks were to be devoted to replication of a single type of experiment in order to obtain sufficient data to allow meaningful interpretation. However, as a lower priority, the reactions of bowheads and white whales to actual helicopter overflights were to be determined if that could be done on occasions when playbacks of drilling platform noise were impractical. The specific 1989 objectives were as follows:

1. To record and characterize the underwater noise from a drilling operation on a grounded ice pad in shallow water during late winter.
2. To measure ambient noise levels and characteristics along the spring migration corridor of bowhead and white whales in the western Beaufort Sea.
3. To measure and model transmission loss of underwater sound along that part of the spring migration corridor, based on playbacks of test tones and the continuous drilling platform sound recorded in (1).
4. To measure the short-term behavioral responses of bowhead and (as possible) white whales visible in open water areas along their spring migration corridor in the western Beaufort Sea to underwater playbacks of the continuous drilling platform sound in (1).
5. To measure the short-term behavioral responses of bowhead and (as possible) white whales visible in open water areas along their spring migration corridor in the western Beaufort Sea to helicopter overflights.
6. To document, as opportunities allow, other aspects of the movements, behavior, basic biology, disturbance responses, and acoustic environment of bowhead 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 effects of the drilling platform sound recorded in (1) on movement patterns and behavior of bowhead 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 at the time of the 1989 field program. It had been hoped to record such sounds in the winter of 1988-89, but no caisson-based drilling was done in the Beaufort Sea during that season. 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.

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 that the most suitable location for playback experiments was about 60 km NE or ENE of Pt. Barrow.

It was hoped that much of the playback work could be done from the edge of the landfast ice. However, ice-based studies of bowheads have not previously been done much to the east of Pt. Barrow. It was realized that it might be impractical to work from the landfast ice edge in that area. Heavy pack ice commonly occurs adjacent to the landfast ice edge, and the whale migration corridor tends to be farther away from the landfast ice edge 60 km east of Pt. Barrow than it is near Barrow. In part because of these anticipated complications, a Bell 212 helicopter was dedicated to the project for the duration of the 1989 field season. This provided the flexibility to work from the pack ice rather than the landfast ice edge when necessary.

In fact, ice conditions east of Pt. Barrow in the spring of 1989 were severe. There was no nearshore lead along the landfast ice edge until 20 May, and there was little open water amidst the pack ice seaward of the landfast ice edge until mid-May. Even after 20 May, when the nearshore lead formed, most of the passing whales moved through the pack ice or along the offshore side of the nearshore lead. Hence, all playback attempts were from the pack ice rather than the edge of the landfast ice. The absence of a consistent whale migration corridor reduced the number of opportunities for observations of whales passing the sound projector. By the last week of May, when weather and ice conditions were greatly improved, few whales were passing. Nonetheless, useful data were obtained on the reactions of bowhead and white whales to drilling noise, and most of the desired physical acoustic data were collected. The availability of full-time helicopter support allowed us to work from different locations on the moving pack ice each day.

The field crew consisted of two teams. ▶ 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). ▶ 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 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. The 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 better vantagepoint for viewing the details of behavior. However, aerial observations were only practical when the cloud ceiling was at least 457 m (1500 ft) above sea level, since bowheads sometimes react to a circling observation aircraft if it flies lower than that altitude.

The helicopter-supported crew worked from the ice on 18 days between 29 April and 30 May 1989. They conducted sound transmission loss experiments on five days, aircraft noise measurements on two days, and projected drilling noise into the water for several hours on each of 11 days. On five of these days, bowhead whales were observed within the area ensonified by the projector. On four days, white whales were also observed near the operating projector. Whales near the operating projector were observed from the ice on two dates, and from both the ice and the air on three dates. Overall, the aircraft crew conducted reconnaissance surveys on 24 days from 1 to 30 May, behavioral observations on 10 days, and photogrammetry on 8 days.

Physical Acoustics

Underwater noise from the *Karluk* drillsite, on a grounded ice pad, was concentrated below 300 Hz. Infrasonic components of the *Karluk* sounds--those below 10 Hz--were not studied, and may have been significant. Most components of the noise above 10 Hz had diminished below background levels after propagating only 2 km through the shallow (6-7 m), ice-covered waters. However, tones at 25 Hz and 294 Hz were still evident at that range.

Underwater noise from aircraft overflights was measured systematically by conducting a series of passes at several altitudes over a pair of hydrophones suspended 3 m and 18 m below the edge of an ice pan. As expected, helicopter noise contained more tonal components than did Twin Otter noise. Helicopter noise was usually stronger at 3 m depth than at 18 m, but this trend was not evident for the Twin Otter. Underwater noise increased and decreased more gradually when the aircraft was high than when it was low. The peak level, recorded when the aircraft was overhead, was higher when the aircraft was low than when it was high. All of these trends are consistent with theory and previous measurements. However, there was evidence that the presence of ice had a modifying influence on some of these trends.

Ambient noise was recorded in small to large open areas amidst the pack ice, and occasionally through thin ice covering recently-refrozen leads. No measurements were obtained during periods of strong wind. The ambient noise was usually dominated by ice noises, wave slap, and marine mammal calls. Bearded seal calls were ubiquitous and often strong; white whale calls were also heard commonly. Bowhead calls were less common. Most measurements of ambient noise were averaged over 8.5 s. Much of the variability in ambient noise, especially above about 500 Hz, was attributable to the variable occurrence and levels of marine mammal calls in these 8.5 s samples.

When no sounds were being projected, tonal sounds from the generator used to power the underwater projector were detectable underwater (18 m deep) at distances as great as 400 m, but not at 1 km. These tones consisted of a harmonic family with fundamental frequency 60 Hz. However, when the projector was in operation, the generator sounds were much less intense than the projected sounds at corresponding frequencies. Hence, the generator would not have been audible to whales during playbacks.

During playback experiments, *Karluk* drilling platform noise was projected into the water at a source level of about 164 dB re 1 μPa. Received levels of the projected drilling noise were strong at distances within ~1 km of the projector. The drilling sound was usually weakly detectable out to distances of about 4-5 km, and occasionally to 9-10 km but not farther than that.

Sound propagation experiments were done on five days, and four of these tests provided interpretable results. Three types of signals were projected using the J-11 projector: pure tones at eight frequencies ranging from 50 Hz to 10 kHz; frequency-modulated tones oscillating within 1/3-octave bands centered at seven frequencies from 50 Hz to 5 kHz; and samples of the *Karluk* drilling sound. During each propagation experiment, underwater sounds were recorded (at 18 m depth) at distances ranging from 100 m to 9 or 18 km. As expected, pure tones often were detectable about twice as far away as were the *Karluk* sounds (typically 9-18 km for tones vs. 4-10 km for *Karluk* sounds). This occurred because all of the projected power was concentrated at a single frequency when tones were projected, but not when broadband drilling sounds were projected. A special matched-filter signal processing technique was effective in measuring received levels of the oscillating tones at distances greater than those where they could be measured by conventional methods.

Semi-empirical Weston/Smith sound propagation models were fitted to the transmission loss data acquired during two propagation experiments. Bottom loss and ice scattering loss coefficients tended to increase with increasing frequency. At frequencies in the kilohertz range, volumetric absorption was also a factor. Underwater sound attenuated more rapidly under pack ice conditions northeast of Pt. Barrow in spring than had been found previously in largely open water conditions in the central and eastern Beaufort Sea during late summer. It is not known whether all of this difference can be attributed to the difference in ice conditions. It may also have been partly attributable to increased bottom loss in our study area. The propagation results from this study were generally consistent with those found during a previous late winter and summer study in the Chukchi Sea.

Bowhead Whales

Movements and General Behavior

Bowheads migrated northeast and east through the study area throughout late April and May 1989, often through heavy pack ice conditions. Even in late May, when a nearshore lead extended east along the landfast ice edge through the study area, the migration corridor 40-80 km ENE of Pt. Barrow was mainly along the offshore side of the lead or through the pack ice north of the lead.

Bowhead calves and their mothers were seen only in the latter half of May in 1989, and constituted the majority of the bowheads present in the last week of May. They did not migrate as strongly or consistently eastward as did other bowheads. A few mother/calf pairs traveled *west* for at least a few kilometers, based on direct observations or photoidentification. One mother/calf pair 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. The calves apparently were pulled along by hydrodynamic forces created by the motion of the mothers. It is not known whether the animals touched one another during this "riding" behavior. Riding has not been seen in late summer or autumn, when the calves are older and larger.

One adult seen on 24 May 1989 was closely accompanied by a presumed yearling.

Photogrammetric data showed that the bowheads without calves present in mid and late May 1989 were mainly adults (>13 m long). The mothers that were measured were 13.9-15.9 m long (n=9); calves were 4.0-5.0 m long (n=8). Four individually-recognizable adults were photographed on two or three different days in May 1989 either by ourselves or by National Marine Fisheries Service personnel. At least four adults photographed by ourselves or NMML in May 1989 had also been photographed in earlier years, including two photographed as early as 1982. One of the latter had a calf in both 1982 and 1989.

Bowheads visible under undisturbed conditions in May 1989, mainly amidst the pack ice, were engaged in traveling (migration), socializing, and resting. Several behaviors that have been observed commonly in late summer and autumn were seen only infrequently in May 1989: pre-dive flexes, fluke-out dives, and aerial activities. A few bouts of sexual activity were observed. Many bowheads apparently migrated through the study area unseen during periods of heavy ice cover and poor weather. It is not known whether the observed frequencies of behaviors in visible whales were representative of frequencies in the population as a whole.

Drilling Noise Playbacks

Because of the difficult field conditions in 1989, there were only five days when we were able to observe bowheads that were 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 too small to allow detailed statistical analysis of acoustic effects on distribution or movements. However, some noteworthy data were obtained.

Several bowheads were observed migrating east past the projector while it was broadcasting continuous drilling sounds. The closest observation was on 19 May, when one bowhead swam almost directly toward the operating projector until it was only 100-120 m away. This whale then dove. The drilling noise :

ambient noise ratios 100-120 m from the projector were estimated to be S:N = 41 dB in the 20-1000 Hz band and S:N = 49 dB in the third-octave band centered at 200 Hz. On the same day, another bowhead swam almost directly toward the projector until it was 720 m away, whereupon it dove and disappeared. Two more bowheads swam past with a closest point of approach 1 km away. All of these positions were determined by theodolite. During this period the sounds received 1.1 km from the projector were monitored via a sonobuoy. The drilling sounds were quite prominent there, well above the natural background noise. Hence, it seems inevitable that all of these whales were able to hear the drilling sounds.

Similarly, on 14 May, at least three migrating bowheads passed as close as 500 m to the side of the projector while it projected continuous drilling sounds, and a fourth passed 900 m to the side. Two of these whales were observed from the circling aircraft for ~1½ hours as they swam NE and N, generally toward the projector. Again, the drilling sounds were monitored 1 km from the projector, and confirmed to be well above background noise levels there. S:N 500 m from the projector was ~13 dB in the 20-1000 Hz band and 24 dB in the third-octave band centered at 80 Hz.

The bowheads mentioned above were migrating NE past the operating sound projector, with no evidence of hesitation or diversion. However, other bowheads may have been diverted when they came that close. On 23 May, we saw a mother and calf swimming north and then west, directly away from the projector, while it emitted drilling noise. They were 1 km away when first seen, and were still heading away when last seen 5 km west of the projector. Below 350 Hz, the drilling noise was quite prominent 1 km from the projector. S:N 1 km from the projector was ~8 dB in the 20-1000 Hz band and 15 dB in the third-octave band centered at 200 Hz. However, it was barely detectable 5 km away, where the whales were still heading west away from the projector.

The westward travel by this pair of bowheads was inconsistent with the normal NE, E or SE movements of bowheads migrating in the study area in spring, and was suggestive of a disturbance reaction. However, we cannot be certain that these whales reacted to the sound projector. Other bowheads, particularly mothers and calves, occasionally traveled west in the absence of drilling noise. It is well known from previous studies that the sensitivity of bowheads to man-made noise varies. It is possible that there is additional variation in sensitivity in spring because some bowheads, before reaching our study area, are pursued by whaling crews. Thus, it would not be surprising if some individual whales migrated past the projector at relatively close distances while other bowheads showed avoidance reactions even to quite weak industrial sounds.

In summary, only limited data have been acquired to date on reactions of bowheads to noise playbacks in spring lead systems. However, some bowheads that were visible migrating through the pack ice east of Pt. Barrow in spring tolerated low-frequency drilling noise without interrupting or diverting their migration. Some bowheads tolerated levels of industrial noise as high as or higher than the levels that elicited avoidance reactions during playbacks to summering bowheads. Other individuals *may* have reacted strongly to drilling noise no stronger than that tolerated by certain bowheads. It would be premature to generalize these few observations. In particular, it should not be assumed that all bowheads migrating in spring would tolerate sounds as strong as those a few hundred meters from the projector. The ice present near all 1989 observation sites made it impossible to determine whether some whales were reacting at greater distances. Also, it should not be assumed that bowheads would behave in the same way when exposed to other types of industrial sounds differing in spectral characteristics or source level.

Aircraft Disturbance

Only a few opportunistic observations of reactions of bowheads to aircraft were obtained in 1989. Our preliminary impression is that bowheads are no more sensitive to fixed wing aircraft like the Twin Otter during spring migration through pack ice than they are in late summer in largely open waters. In the one observed case of repeated exposure to low-altitude helicopter passes, a mother and calf bowhead did not flee, but may have dived in response to some passes. No generalizations should be drawn from these preliminary data on reactions to helicopters.

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.

Most white whales were either migrating in a generally NE direction or resting on the surface. Migrating white whales tended to follow leads or cracks, changing heading as necessary to remain within the crack. Several groups of white whales were seen resting quiescent beneath the thin ice covering recently-refrozen cracks amidst heavy pack ice. In one case, a group of ~25 white whales vigorously swam back and forth between two holes ~15 m apart, apparently trying to keep the holes from freezing over.

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 of the operating projector, including a few within 50-75 m of the projector. 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 visual cues) at distances on the order of 200-400 m.

On 14 May, 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 of it.

We saw no evidence that white whales reacted at distances greater than 200-400 m. We suspect that this was related to their poor hearing sensitivity at the low frequencies where the *Karluk* drilling sounds were concentrated. On most days during the study, received levels of the low-frequency drilling sounds (on a 1/3-octave basis) were less than the measured hearing sensitivity of white whales at all distances beyond ~200 m. This suggests that white whales may have been unable to hear the low-frequency drilling sounds at distances much beyond 200-400 m, even though the sounds were detectable by hydrophones (and audible to humans) up to several kilometers away.

These results provide preliminary evidence about the seemingly low sensitivity of white whales to the one type of continuous drilling sound used in the 1989 experiments. However, the sample sizes were small. Also, the results refer to a particular experimental situation. Some oil industry activities have higher source levels than we could simulate with a J-11 sound projector. Reaction distances are expected to be greater in such cases. Some other activities have lower source levels than did the J-11 projector.

Also, sensitivity of white whales to other types of oil industry sounds probably differs. The hearing sensitivity of white whales improves greatly with increasing frequency. Thus, reaction distances are likely to be greater in the cases of industry noises containing higher frequency components. In the Canadian high arctic, spring-migrating white whales react strongly to noise from vessels tens of kilometers away. 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.

Aircraft Disturbance

Only a few opportunistic observations of the reactions of white whales to aircraft overflights were obtained in 1989. *Twin Otter*: Two white whales rolled slightly and looked up at the Twin Otter as it flew over at altitudes of 260 and 457 m ASL. A group of seven white whales dove abruptly and steeply when it flew almost directly over them at 200 m. *Bell 212*: Two groups of white whales dove immediately when the helicopter flew over at altitudes of 152 and 457 m ASL. A single white whale dove rapidly and steeply when the helicopter flew 50 m to the side at 120 m ASL. Additional data are needed before conclusions can be drawn about reactions of white whales to aircraft overflights during spring migration through the study area.

Prior to the 1989 field season, doubts had been expressed about the feasibility of a study of this type, given the logistical problems and potential for interference with whaling or other research programs. The initial 1989 phase of the study demonstrated that it is possible to conduct an experimental study of noise effects on whales migrating through leads in spring, and to do so without interfering with spring whaling.

Of the four general objectives stated above, objectives 1-2 were partially met, but additional data are needed. Objective 3, involving coordination with other studies and local resource users, was met. Objective 4 concerned analyses and hypothesis tests; the 1989 data have been analyzed, but formal tests of hypotheses have been deferred because of the generally low sample sizes from the 1989 experimental work. Sample sizes were small because of the difficult ice and weather conditions encountered in 1989. In a year with different weather and ice conditions, considerably larger sample sizes might be obtained.

After additional data are collected, the results of this study should be useful in assessing the acoustic effects of oil exploration and development near spring lead systems on migrating bowhead and white whales. These results should help resolve questions about possible jeopardy to bowheads if oil development proceeds near spring leads.

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Mr. Allen Milne	Sci. Rev. Board Chairman,
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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).

All of the bowhead disturbance studies done to date have 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 has 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 has been no systematic scientific study of the suggestion by Inupiat whalers that bowheads 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 (Richardson et al. 1983; Greene 1987a). 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). 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. 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). Their responsiveness 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 the first year of a continuing study. Fieldwork in 1989 provided useful data concerning several of the objectives. However, more data will be required before definite conclusions can be drawn about disturbance effects on spring-migrating bowheads and white whales.

Background

Spring Migration of Bowhead Whales

Bowhead whales spend the winter in and near the pack ice of the western Bering Sea from St. Lawrence Island south to St. Matthew Island and west to the USSR coast (Braham 1984). They leave their wintering grounds in March and follow the nearshore flaw lead ("NW Alaska Lead") through the Chukchi Sea to Point Barrow (Fig. 1; Ljungblad et al. 1985). Although a few sightings have been made at the Barrow ice-edge as early as March (Brower 1942; Dronenburg et al. 1983), the main migration usually does not begin until late April. The majority of bowheads pass Pt. Barrow and enter the Beaufort Sea during May but some stragglers continue passing until mid- to late June (Fig. 2). The early migrants tend to be small whales and the later migrants tend to be large ones, including mothers with newborn calves (Nerini et al. 1987).

In 1980, unusually severe ice conditions in the Bering Strait region apparently blocked the migration route of bowheads until mid May (Johnson et al. 1981). Although the first bowhead was not seen passing Pt. Barrow until 21 May (~1 month late), the majority of the whales had passed Barrow by early June--the normal end time of the migration past Barrow.

The direction of movement of bowheads appears to turn slightly from northeast to ENE or east after they pass Pt. Barrow (Marko and Fraker 1981; Braham 1984; Ljungblad et al. 1985; Rugh 1987). The turning point tends to be about 35 km beyond Pt. Barrow, where the landfast ice edge also tends to turn from NE to about east or ESE. Once east of Pt. Barrow, most bowheads follow the "E-W offshore shear zone" through the pack ice rather than the nearshore flaw lead along the edge of the landfast ice (Fig. 1, 3). The whales are more dispersed there than when they are southwest of Barrow, and bowheads are frequently found among the pack ice (Ljungblad et al. 1985). As bowheads move eastward their

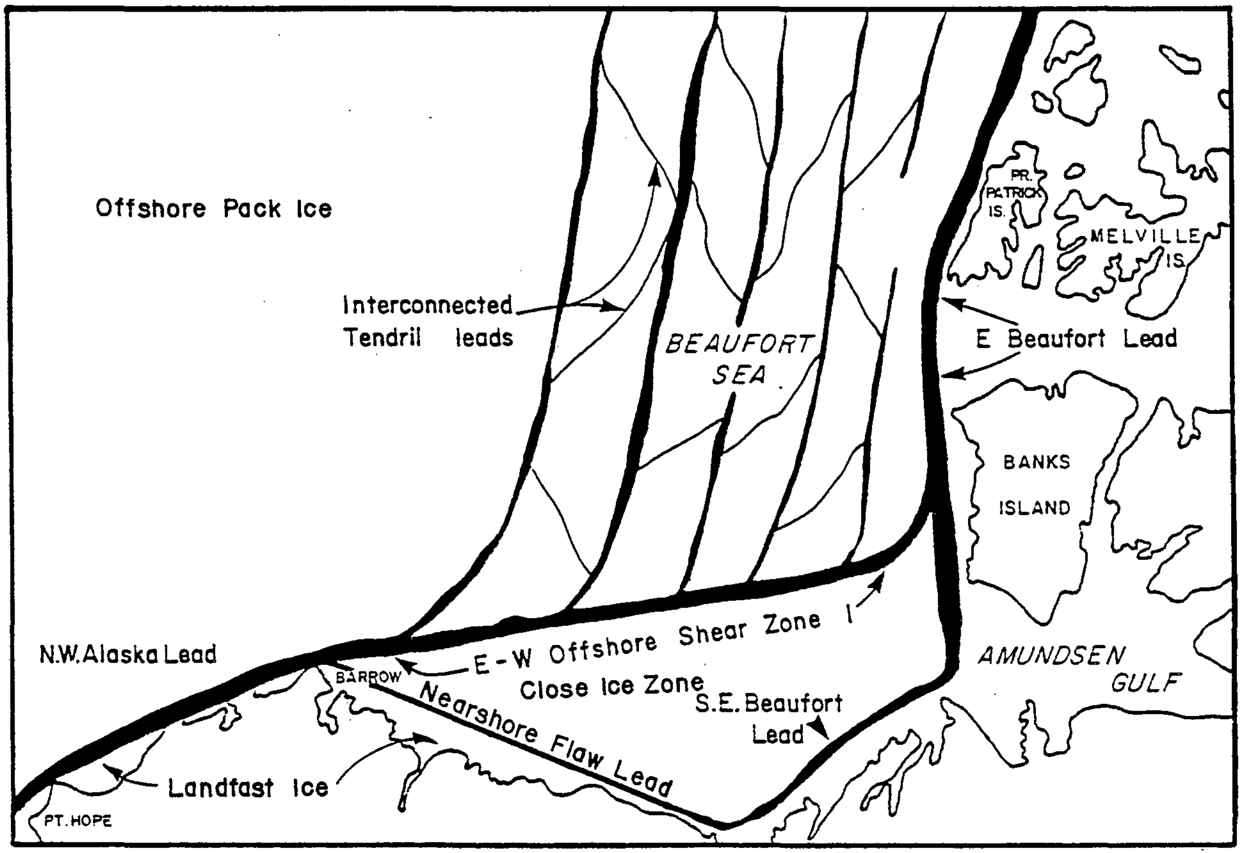


Fig. 1. Typical pattern of spring lead formation in the Beaufort Sea (modified from Marko and Fraker 1981).

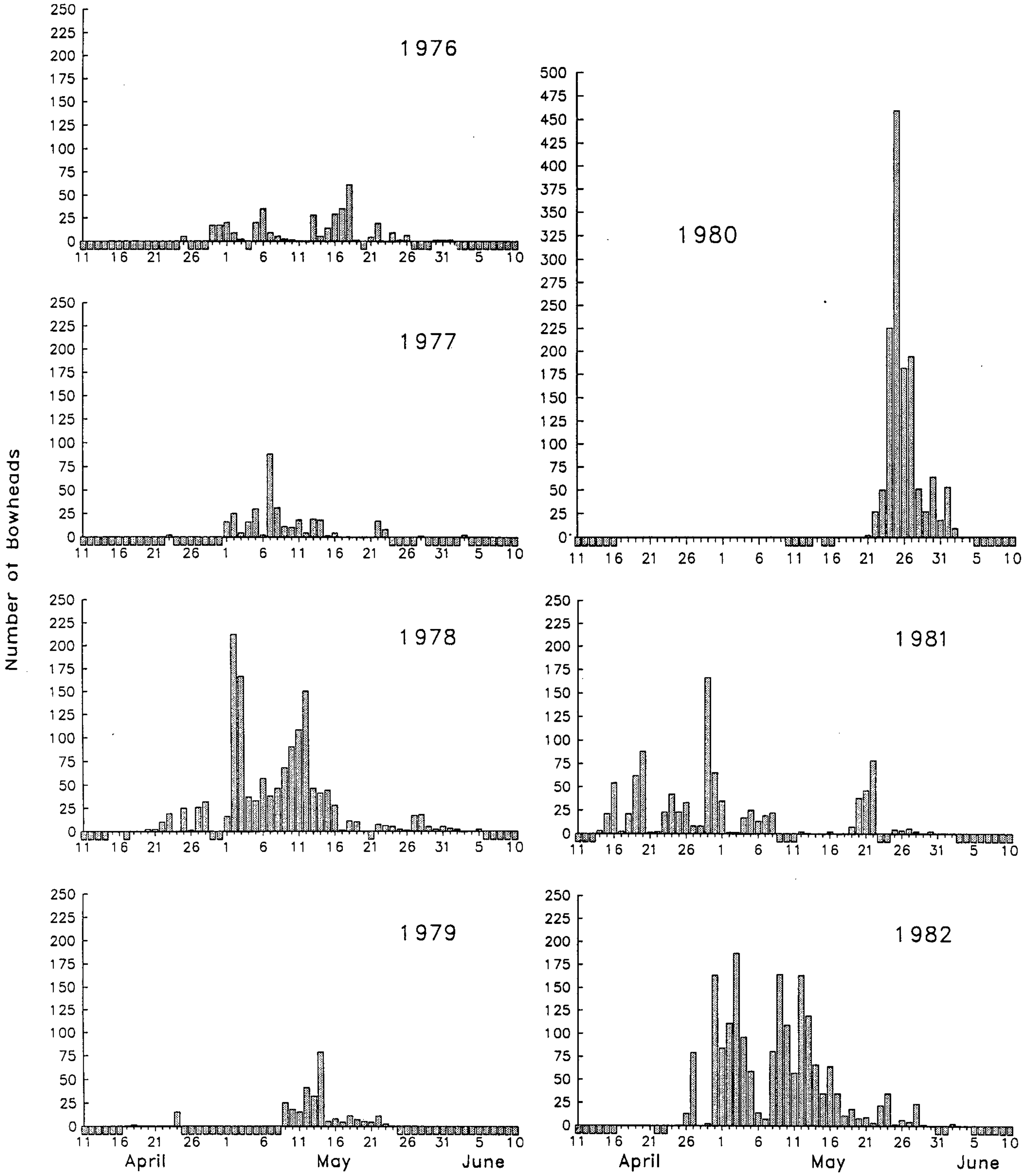
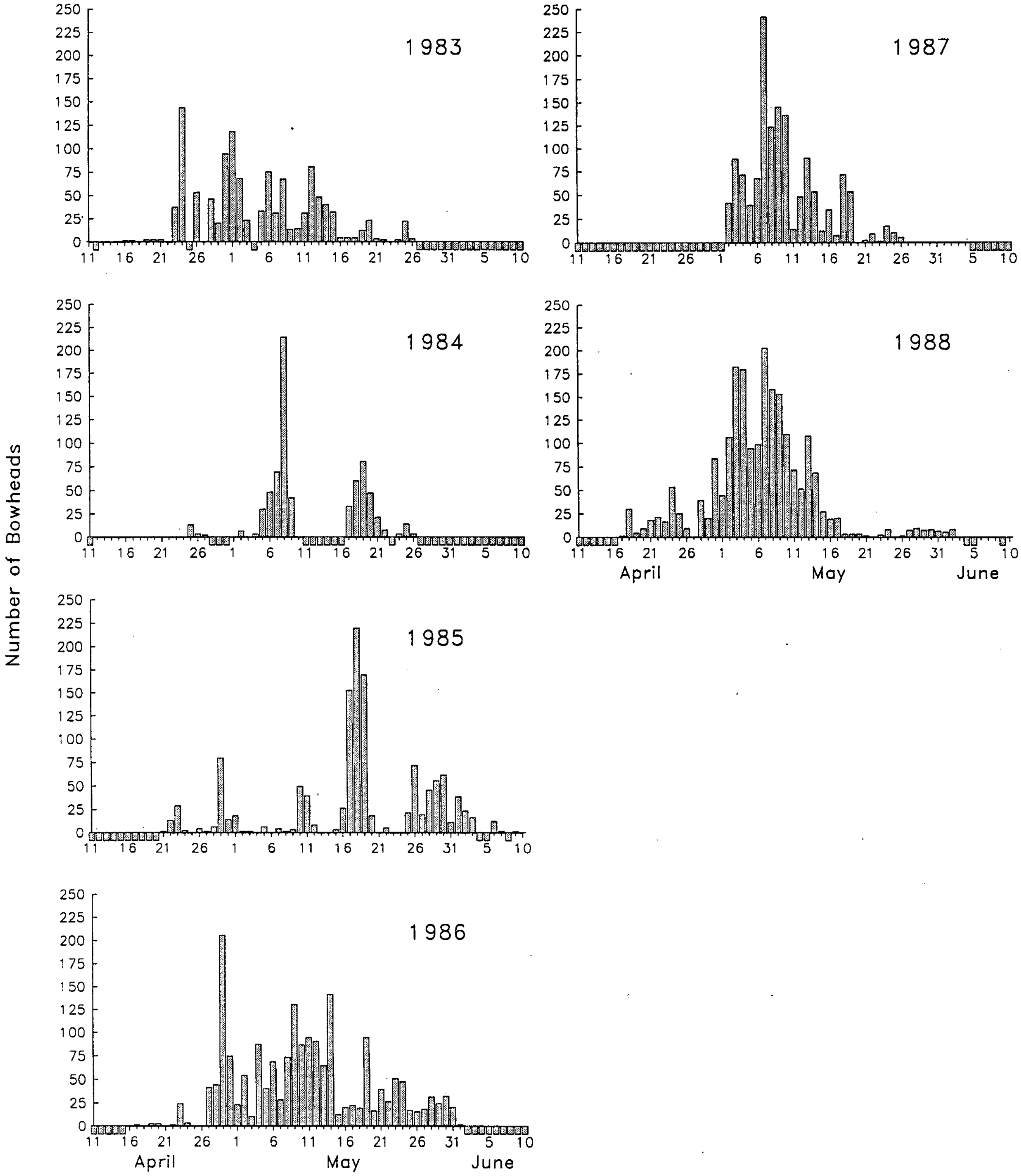


Fig. 2. Timing of the spring bowhead migration past ice-based census camps near Barrow, 1976-88. Days when no visual census was possible are shown by a mark below the date axis. Replotted from a data file provided by North Slope Borough Dept. of Wildlife Management, courtesy of J. C. George.



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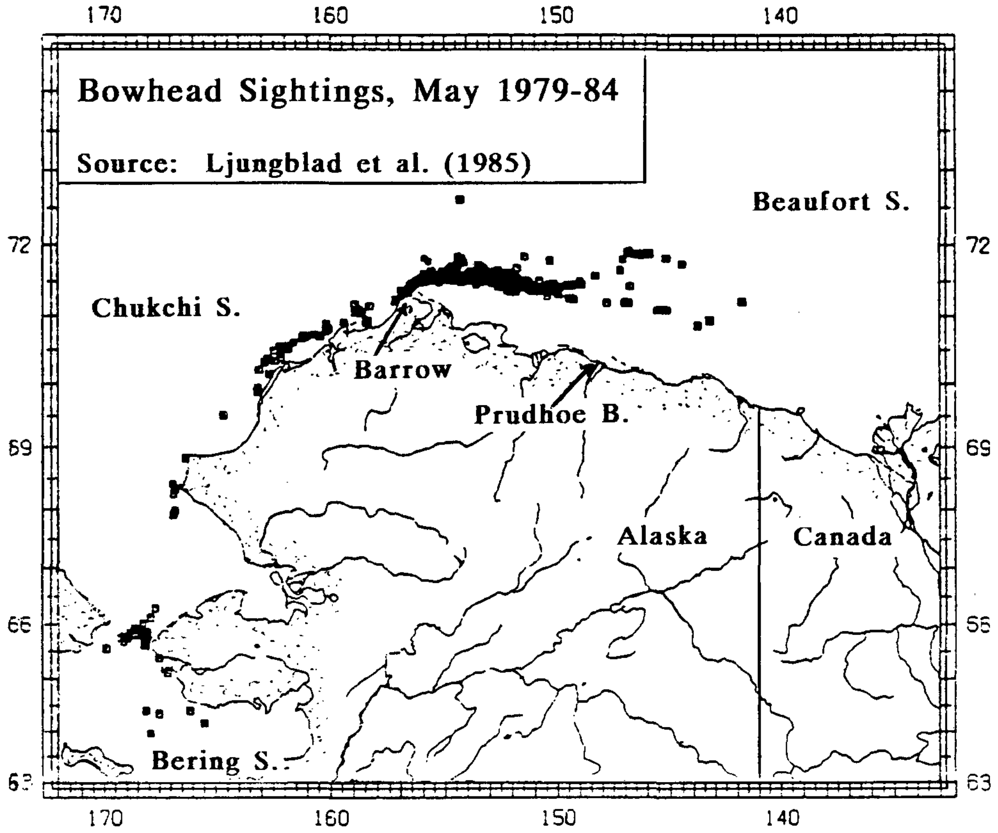


Fig. 3. Distribution of bowhead whale sightings during the month of May in 1979-1984 (modified from Ljungblad et al. 1985).

migration corridor becomes wider and they are more likely to be found amidst the pack ice both north and south of the main shear zone (Marko and Fraker 1981). Ljungblad et al. (1984) found the eastward migration route to be ~25 km wide at Barrow but ~50 km wide from north of Smith Bay to Harrison Bay.

The width of the spring migration route through the planned study area east of Pt. Barrow varies from year to year. Locations where bowheads were sighted during surveys flown by the U.S. National Marine Fisheries Service during the springs of 1985-87 are shown in Figures 4A-4C. The migration corridor in 1987 was narrower than the corridors in 1985-86. In 1987, the corridor was apparently less than 11 km wide even as much as 50 km east of Pt. Barrow (Fig. 4C). In each of these years, there was a concentration of bowheads along a route oriented ENE from Pt. Barrow, gradually turning to the right as the whales progressed eastward.

All available evidence indicates that few if any bowheads migrate in the "Nearshore Flaw Leads" that occasionally form along the landfast ice edge off the NE Alaska coast (Fig. 1). Almost all travel east through leads in the E-W offshore shear zone.

Spring Migration of White Whales

White whales winter among the pack ice of the Bering and southern Chukchi seas (Seaman et al. 1985). They begin their migration one to two weeks earlier than bowheads (Braham et al. 1984). The earliest recorded passage of white whales past Point Barrow was on 2 April, but white whales are known to utilize offshore leads during spring migration and it is possible that some pass Pt. Barrow unnoticed on earlier dates. Frost et al. (1988) suggest that they may pass Barrow as early as late March. The peak of the spring migration past Pt. Barrow occurs from late April to the third week of May, and varies according to ice conditions. The spring migration past Pt. Barrow may continue through at least early July (Oliver 1987).

White whales follow the nearshore flaw lead through the Chukchi Sea to Pt. Barrow (Ljungblad et al. 1985), and are more likely to move through the offshore pack ice than are bowheads (Braham et al. 1984). Once they have passed Pt. Barrow, white whales follow offshore leads in deep water northeast or east toward Banks Island (Fig. 1, 5; Fraker et al. 1978; Hazard 1988; Fraker 1979). They tend to migrate in waters north of the usual bowhead migration route, although there is some overlap. Ljungblad et al. (1984) referred to the distribution of the two species east of Pt. Barrow as "partially segregated" with white whales commonly seen farther north than bowheads. Braham et al. (1984) found white whales near the northern ends of survey lines flown north of Pt. Barrow in May 1976 (sightings near 72°10'N), and as far north as ~73°15' northeast of Pt. Barrow in late May 1977. The latter sighting was about 300 km north of the coast between Harrison and Prudhoe Bays. Farther east, in the Canadian Beaufort Sea, Fraker (1979) found white whales as far north as he flew (75°36'N), and he suggested that some white whales could move through waters as far north as 77°N. Frost et al. (1988) mapped spring white whale sightings in

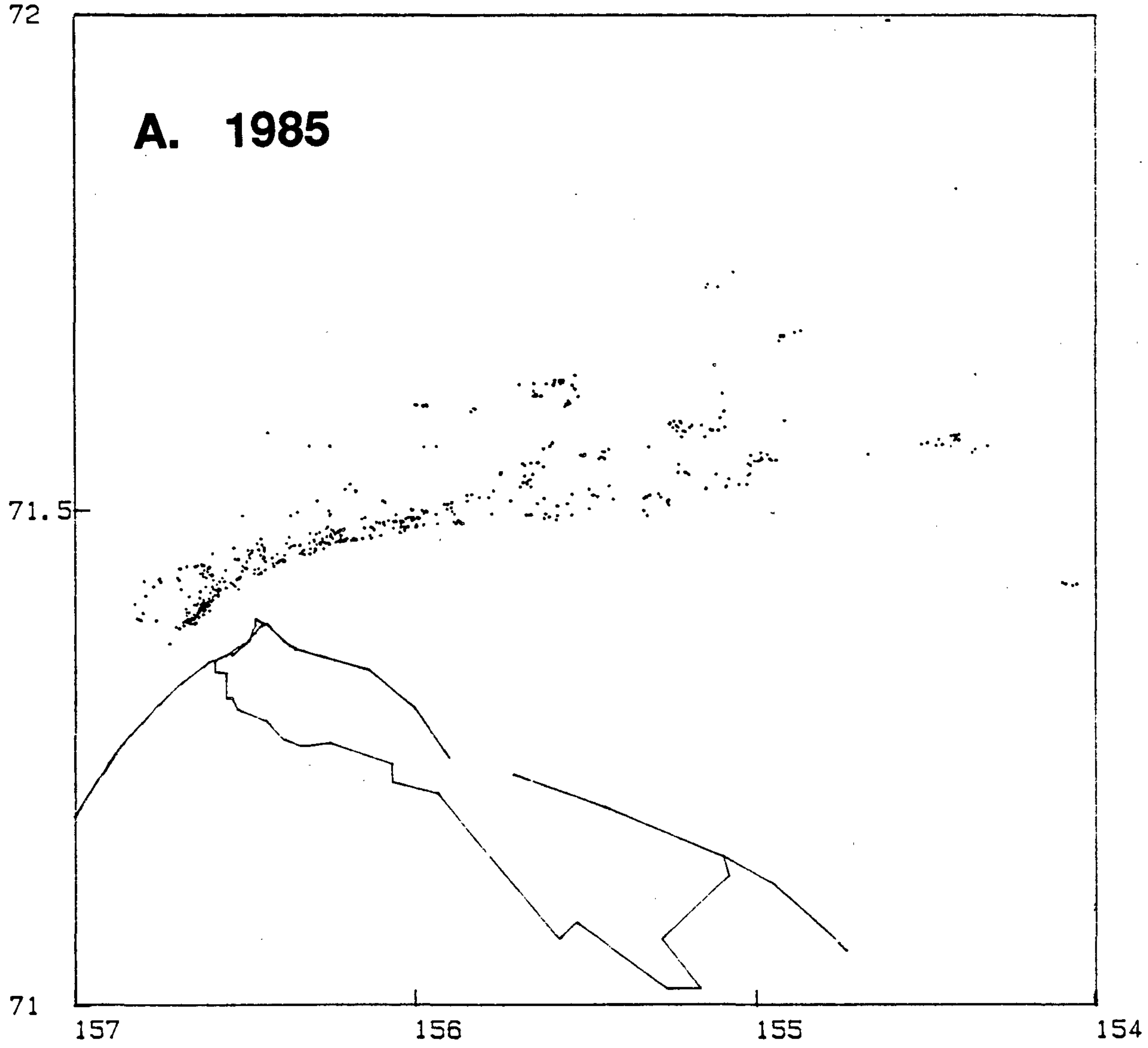
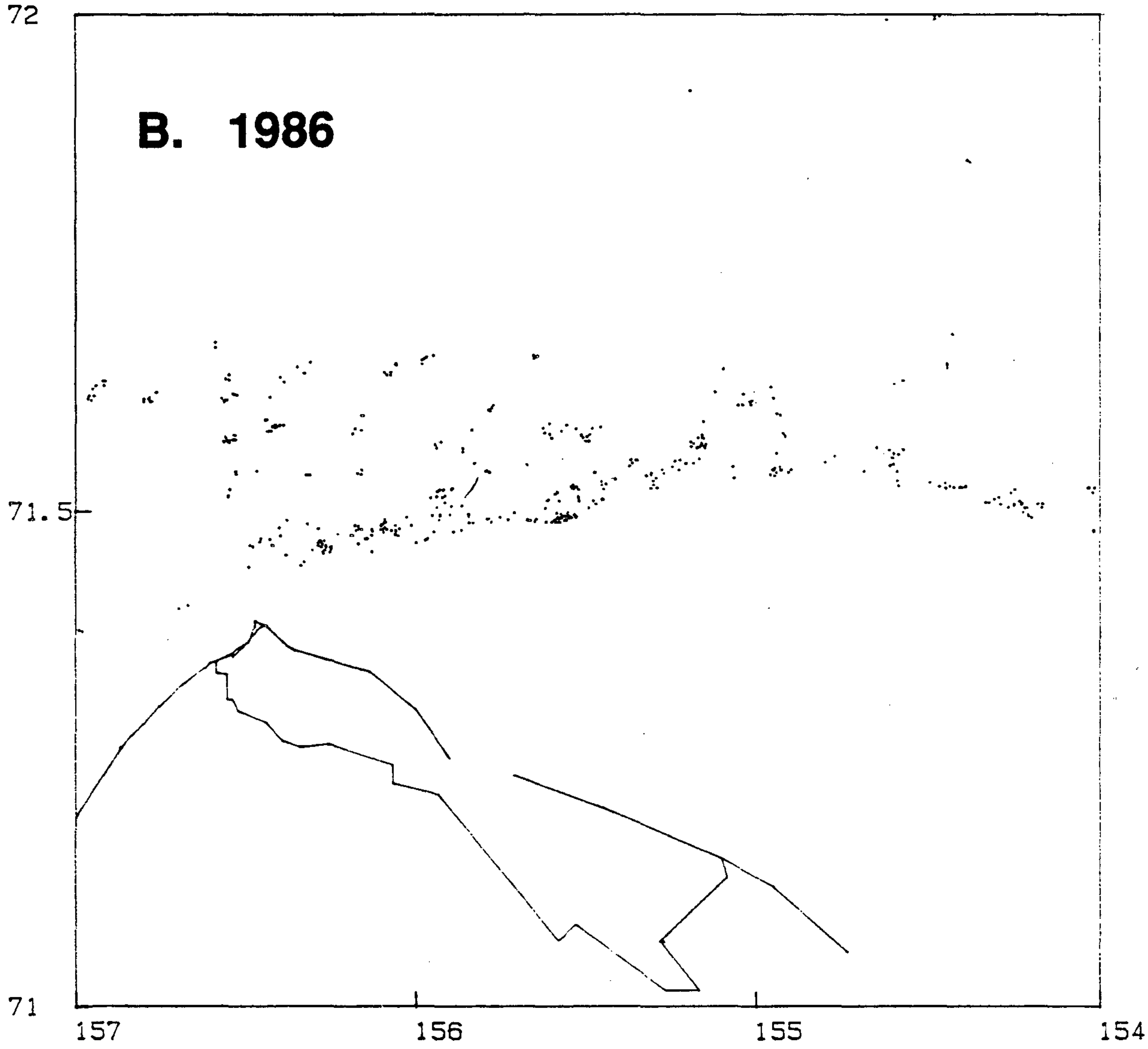


Fig. 4. Locations where bowheads were photographed during spring photogrammetric surveys conducted by the U.S. National Marine Fisheries Service in (A) 1985, (B) 1986, and (C) 1987 (NMFS unpubl. data).



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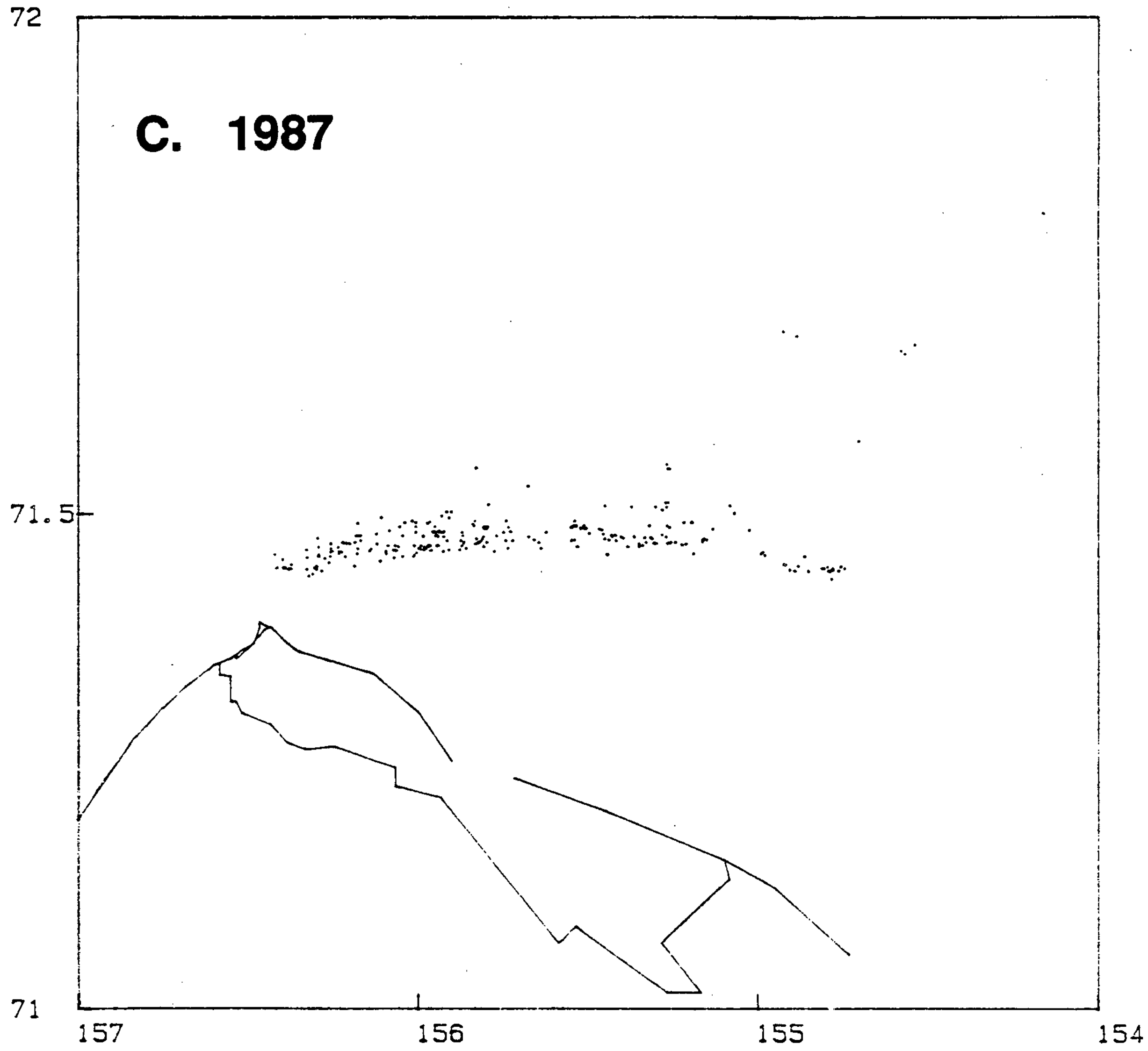

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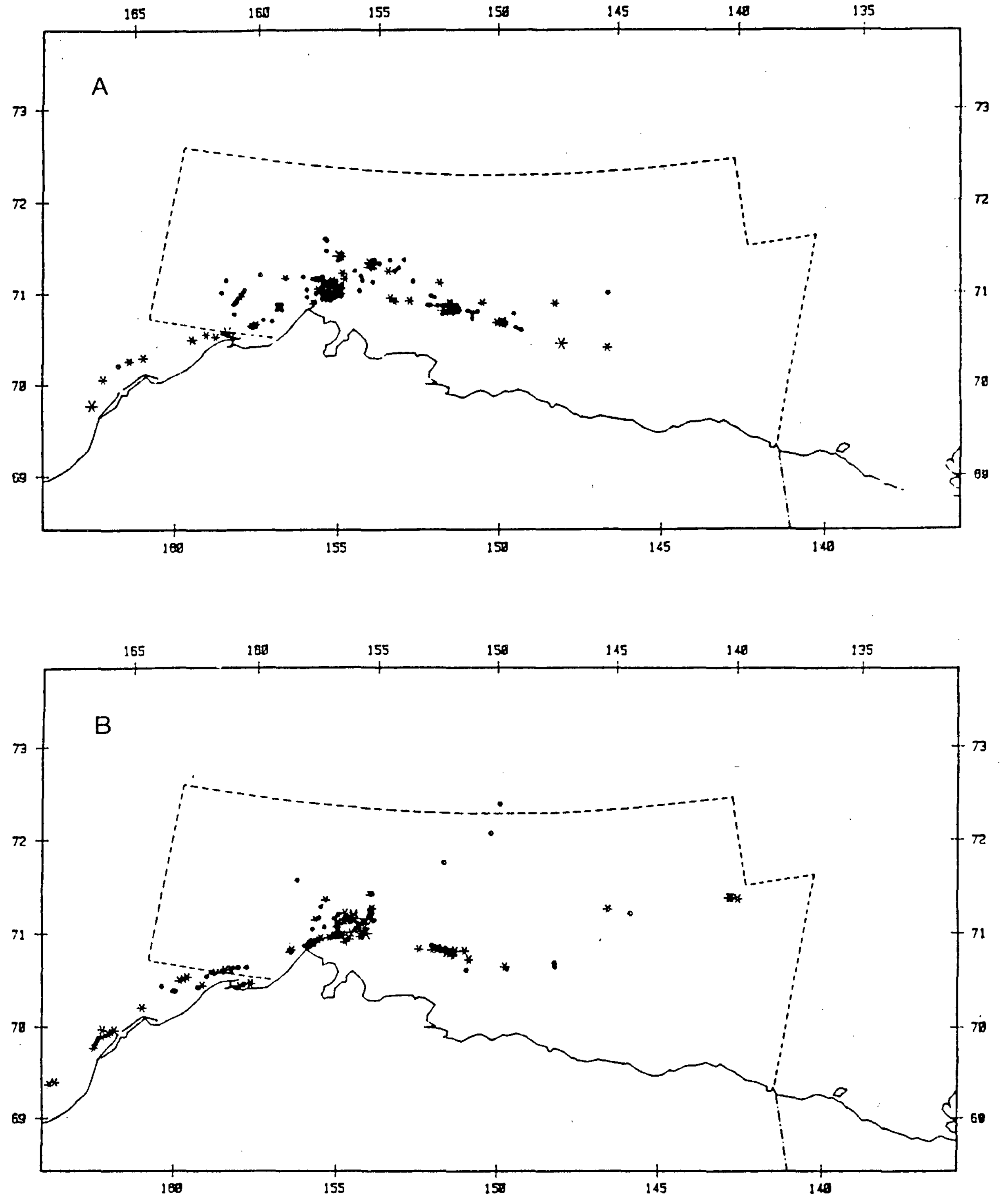

Fig. 5. Distribution of white whale sightings during (**A**) 1-15 May and (**B**) 16-31 May in the Alaskan Chukchi and Beaufort Seas (from Frost et al. 1988).

the Chukchi and Alaskan Beaufort Sea by two-week periods (Fig. 5). These maps also indicate a migration path somewhat farther north and more dispersed than the relatively narrow bowhead migration corridor. The scarcity of white whale sightings north of 72°N on Figure 5 may, in part, reflect little survey coverage in that area.

Disturbance Reactions of Bowhead Whales

The short-term behavioral reactions of bowhead whales to several types of oil industry activities have been studied on the summer feeding grounds in the eastern Beaufort Sea (Richardson et al. 1985a,b, 1986, 1990; Wartzok et al. 1989) and during autumn feeding and migration in the Alaskan Beaufort Sea (Reeves et al. 1984; LGL and Greeneridge 1987; Ljungblad et al. 1988). The major types of oil industry activities whose disturbance effects have been investigated are aircraft and vessel traffic (including, to a limited extent, icebreakers), marine seismic exploration, drillships, and offshore construction. These and other related studies have included work on the spectral characteristics, source and received levels, and propagation losses of the underwater noise from each of the main oil industry activities occurring in the Beaufort Sea during summer and autumn.

The summer/early autumn data from the eastern Beaufort Sea came from very different circumstances than those found in spring. The data came from areas of open water or, at most, loose pack ice, and involved whales that were remaining in specific feeding areas rather than actively traveling. However, the eastern Beaufort work is noteworthy in that it did involve controlled experiments on the reactions of bowheads to continuous industrial sounds. Recorded drilling and construction sounds were projected into the water, and the behavior of bowheads before, during and sometimes after the playbacks was compared (Richardson et al. 1985b, 1990; Wartzok et al. 1989). However, the durations of the experiments were limited to 30-105 min by logistical constraints, and the sound levels emitted during these tests were less than those of the actual industrial activities being simulated.

The bowhead disturbance data acquired during summer (up to 1985) have been used, along with data on underwater noise from oil industry activities, to predict the likely radii of audibility and responsiveness around various oil industry activities (Miles et al. 1987; Richardson et al. 1990). These predictions refer to late summer conditions in the Canadian Beaufort and early autumn conditions in the Alaskan Beaufort. The Miles et al. modeling study assumed that each industry activity operated during autumn, in turn, at each of six specific drillsites in the Alaskan Beaufort Sea.

The available data on disturbance reactions of bowheads during autumn migration may be the most relevant results with respect to spring migration. LGL and Greeneridge (1987) studied the reactions of bowheads to full-scale drilling operations involving a drillship and several support ships. Drilling activities of this nature may be more disruptive to whales than production activities from a single stationary platform. LGL and Greeneridge (1987) found that westward-migrating bowheads whose courses would have brought them within 10 km of the drillship altered course to pass more than 10 km north or south of the drillsite. By making such a diversion, they avoided exposure to strong industrial noise. Several migrating whales were observed 15-30 km from the drillsite. Their responses to the weaker noise at those ranges were described as none to mild. On one occasion, a bowhead altered its course repeatedly, apparently to divert around the drillsite. It remained 23-27 km from the drilling operation as it migrated westward past the operation. In spring, ice conditions might often prevent bowheads from undertaking similar diversions. In that case, it is unknown how the whales would react.

There have been a few late winter and spring observations of bowhead reactions to fixed wing survey aircraft (e.g. Ljungblad et al. 1984; Ljungblad 1986) and helicopters (Dahlheim 1981). With these few exceptions, there is virtually no information in the scientific literature concerning the reactions of bowheads to human activities and noise in spring.

Thus, previous disturbance studies of bowheads have been important in assessing potential short-term disturbance responses, at least in the open water and loose ice conditions common in summer and early autumn. However, available data are not sufficient for predicting short-term reactions of bowheads in spring when ice conditions and whale activities are very different. Existing data also are not sufficient for predicting the long-term consequences of continuous, stationary industrial activities at any season, and especially in spring.

Disturbance Reactions of White Whales

Davis and Thomson (1984) and Richardson et al. (1989) reviewed the available published and unpublished information on responses of white whales to disturbance. There is great variation in responses depending on the population involved, time of year, and other factors such as presence of potential food.

Populations that have been exposed to moderate to high levels of shipping in open water seem to have habituated to the shipping noise. White whales in areas with much vessel traffic (St. Lawrence estuary; Cook Inlet, Alaska; Churchill, Manitoba) are not displaced by nearby shipping or by oil production facilities (Davis and Thomson 1984). In the Bristol Bay area (Alaska), white whales were relatively insensitive to playbacks of taped drilling noise from a semi-submersible vessel, although they did "startle" when the playback started and stopped suddenly. However, white whales responded more noticeably to outboard motor noise, perhaps because whales are hunted from outboards (Stewart et al. 1982, 1983; Awbrey and Stewart 1983). Playbacks of drilling noise to captive animals caused little behavior change and no evidence of physiological stress even though received levels were as high as 153 dB re 1 μPa (Awbrey et al. 1986). The latter study, along with Johnson et al. (1989), also confirmed that hearing sensitivity below 1000 Hz, where industrial noise is concentrated, is quite poor even though white whales have very sensitive hearing at high frequencies (Fig. 6).

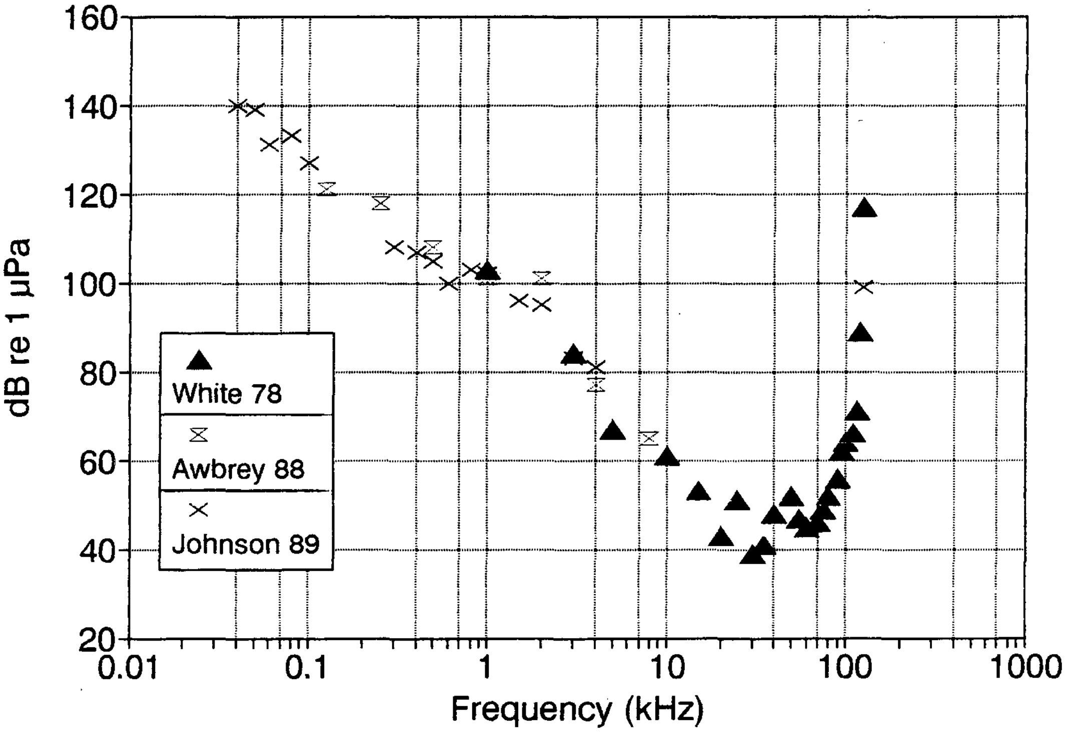

Fig. 6. Absolute hearing sensitivity of white whales listening underwater, plotted in relation to frequency. Data are from White et al. (1978, average of two animals), Awbrey et al. (1988, n = 3), and Johnson et al. (1989, n = 1).

In addition to general habituation, the activity of the animals may affect their response to disturbance. White whales actively feed on salmon in inner Bristol Bay in June and early July. The area contains a major salmon fishery with hundreds of fishing boats supported by high-powered tender boats and float planes. While feeding on the salmon, the whales consistently move among the boats and nets (Frost et al. 1983; L. Lowry *in* Davis and Thomson 1984). It appears that feeding white whales will sometimes tolerate large amounts of noise and disturbance.

Ice conditions apparently can influence the disturbance responses. In open waters of the Mackenzie estuary, white whales were relatively tolerant of stationary noise sources, although they did take evasive action at distances up to 2.4 km from moving vessels. White whales seemed more sensitive when in confined areas, such as leads in the ice, than when in open water. They also appeared to be more sensitive in shallow than in deeper water (Fraker 1977a,b, 1978; Fraker and Fraker 1979; Norton Fraker and Fraker 1982; M.A. Fraker *in* Davis and Thomson 1984).

In the Canadian high arctic, white whales of a different stock are very sensitive to ship noise when the first ship of the season approaches (LGL and Greeneridge 1986; Cosens and Dueck 1988). Alarm calls and fleeing responses were detected when the ship was still tens of kilometers away and its sound was barely detectable. These extremely large reaction distances may have been partly attributable to good sound propagation conditions in deep water. However, other reasons for the high sensitivity of the whales may have included the partial confinement of the whales by heavy ice cover in spring, and the novelty of industrial noise in that area and season. These last two possibilities might also apply in the Beaufort Sea in spring.

To summarize, available data show that reactions of white whales to man-made noise are highly variable. Based on these data, it is not possible to predict how white whales migrating through the ice near Barrow will respond to playbacks of industrial noise. Available data suggest that white whales whose movements are partly confined by ice in spring may be quite sensitive to industrial noise.

Sounds from Spring Production Activities

There are published data on the spectral characteristics and levels of underwater noise from many activities of the offshore oil industry. Many of these measurements were obtained in the Beaufort Sea or elsewhere in Alaskan waters. However, offshore oil production has not yet begun from arctic waters deep enough to be used by bowhead whales, so there are no data on noise from oil production activities in the arctic.

Sounds from production platforms were studied by Gales (1982), but the types of platforms that he studied are not at all typical of those that would be used in arctic waters. Future hydrocarbon production near the spring migration routes of bowheads and white whales in the arctic is likely to be from large, bottom-founded caissons or islands. These structures, unlike those studied by Gales, are expected to have large areas of contact with the bottom in order to withstand expected ice conditions. Sounds from bottom-founded exploration caissons have been recorded in the Canadian and Alaskan Beaufort Sea. Almost all published results concern the open water season (Greene 1985, 1987b; Miles et al. 1987; Hall and Francine 1990).

Existing bottom-founded drilling platforms used in the arctic (CIDS, Molikpaq, SSDC) are usually encircled by a grounded mass of ice when operating in winter. This ice is seeded by hoses from the platform in order to build up a thick barrier around the structure. This barrier provides additional protection against moving pack ice. The presence of this ice barrier may significantly reduce the amount of noise that radiates into the waters surrounding the drilling platform. Thus, sounds from summer drilling operations may be quite different than noise from winter/spring drilling operations even if conducted from the same platform.

The only data on sounds emitted by a bottom-founded platform surrounded by ice were recorded near the CIDS in late November 1989, after the present study was conducted (Hall and Francine 1990).[1] The received broadband levels in the 30-1000 Hz band were relatively low (~89 dB re 1 μPa at range 1.4 km). However, there was much more energy at frequencies below 30 Hz, including a strong tone near 1.5 Hz. That tone was interpreted as being the fundamental frequency of the rotary table on the drillrig. Other studies of noise from industrial activities in the Beaufort Sea have not considered sound components below 10 or 20 Hz. It is not known whether bowheads are sensitive to frequencies in this range (see p. 208-210). White whales almost certainly do not have useful sensitivity below 20 Hz, based on measurements from 40 Hz upward (Fig. 6).

Offshore production platforms typically support many directionally-drilled wells. Drilling of additional wells may continue long after production from the first well begins. Hence, it would be reasonable to study the reactions of whales to sounds from existing bottom-founded drilling caissons used in the arctic, even though these structures are not fully equivalent to anticipated production facilities.

The attenuation of received noise levels with increasing distance from industrial sources has received considerable attention in arctic waters. However, most of these data were acquired during seasons other than spring, and very few of the published propagation data were obtained near Barrow. Seasonal variations in ice conditions and water mass characteristics are known to have strong effects on underwater sound propagation in the arctic. A review and

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[1] Greeneridge Sciences was funded, under the present project, to obtain such recordings during the winter of 1988-89 if a caisson had been drilling in the Alaskan or Canadian Beaufort Sea at that time. However, there were no caisson-based drilling operations in the Beaufort Sea during that winter.

analysis by BBN Systems & Technologies Corp. during the planning phase of this project indicated that propagation conditions in and near spring lead systems vary widely, depending largely on variable ice characteristics (Appendix A).

Objectives

General Objectives

Given the above concerns and data gaps, 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 Seas 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."

Specific 1989 Objectives

Prior to the 1989 field program, it was decided that the study would include at least a second spring field season, in 1990. It was recognized that the overall objectives could not be met in a single season. The highest priority during the 1989 field program 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.

The specific objectives for the first field season, in 1989, were as follows:

1. To record and characterize the underwater noise from a drilling operation on a grounded ice pad in shallow water during late winter.

2. To measure ambient noise levels and characteristics along the spring migration corridor of bowhead and white whales in the western Beaufort Sea.
3. To measure and model transmission loss of underwater sound along that part of the spring migration corridor, based on playbacks of test tones and the continuous drilling platform sound recorded in (1).
4. To measure the short-term behavioral responses of bowhead and (as possible) white whales visible in open water areas along their spring migration corridor in the western Beaufort Sea to underwater playbacks of the continuous drilling platform sound in (1).
5. To measure the short-term behavioral responses of bowhead and (as possible) white whales visible in open water areas along their spring migration corridor in the western Beaufort Sea to helicopter overflights.
6. To document, as opportunities allow, other aspects of the movements, behavior, basic biology, disturbance responses, and acoustic environment of bowhead 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 effects of the drilling platform sound recorded in (1) on movement patterns and behavior of bowhead 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 in 1989 were made more specific in four areas: (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.

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. is responsible for sound propagation modeling.

The contract was awarded to LGL in the autumn of 1988. 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.

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; 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. (The report by Malme et al. (1989) is included as Appendix A of the present report.) 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) 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 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.

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, 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, 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 (457 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 are used in modeling studies to estimate sound levels at various distances from noise sources under different ice conditions.

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 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 ENE 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 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 results to the Chukchi Sea is not verified, since all 1989 data were necessarily obtained well to the ENE of Pt. Barrow in the western Beaufort Sea. (However, see p. 148.)
>
> (c) Water depths at many of the 1989 study locations were greater than those where bottom-founded drilling or 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 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, p. 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.

(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, 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. 1990). Nonetheless, any extrapolation of the 1989 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, 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 provided a reasonable simulation of the components of *Karluk* sound within the 50 to 12,000 Hz band. However, the playback system could not adequately reproduce components at frequencies much below 50 Hz (p. 99). White whales are not sensitive to these low frequency components unless their levels are very high (Fig. 6), so 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. 1990). This suggests that playbacks can provide relevant data.

(4) It is assumed that the presence of the observers did not bias the results. 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 low:

Limitations: (a) Whales are known to react to aircraft overflights in some situations; most 1989 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 457 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. 1989). Limited data from the 1989 study suggest that sensitivity to aircraft is no greater in spring than during summer or autumn (see p. 210 and 239). Given this, and the fact that we excluded observations from periods when the aircraft was below 457 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 bias that does exist can be avoided by comparing behavior of whales passing the camp when the projector is operating vs. silent. (This type of control is scheduled for the 1990 field season.)

(c) It was necessary to operate a small gasoline-powered generator at the ice camp during playbacks and some control periods. This emitted some 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. 97).

(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 that they can be seen below the surface throughout part or all of a dive in open water.

(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 (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

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, and 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 undoubtedly 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.

In addition, for more than a decade there has been an annual spring bowhead census near Pt. Barrow (Fig. 2). In 1988, a very intensive census effort was conducted, and in 1989 a scaled-down census effort was planned for late April and May. 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 the distribution of migration directions. Any one of these changes could significantly affect the results of the census. Also, acoustic monitoring techniques are now an important part of the census (Clark et al. 1986; Ko et al. 1986; Gentleman and Zeh 1987). 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 the preceding "Background" section. Logistically, the most advantageous location for the study area and ice camp were expected to be along the landfast ice edge where a permanent camp could have been established. However, Miller (1989) noted that open leads are found infrequently along the landfast ice edge east of Barrow, and that the migrating bowheads start to move away from the landfast ice edge about 35 km ENE of Pt. Barrow. Beyond that point, the whales tend to follow the E-W offshore shear zone rather than the nearshore flaw lead along the landfast ice edge (Fig. 1). The white whale migration corridor is broader; it overlaps with the corridor used by bowheads but also extends farther offshore. Thus, few whales are found along the landfast ice edge more than about 35 km east of Barrow.

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 along the E-W offshore shear zone NE 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, and logistic support becomes progressively more difficult.

Given the above, it was clearly 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 (Appendix A) and consultation with local Barrow organizations, individuals and scientific investigators. 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).

Because of the 60 km restriction, there were several days during the first half of the study when playbacks of drilling sounds could not be done even though open water and whales were present closer to Barrow. On some of these latter occasions we conducted aerial observations of bowhead behavior and/or aerial photogrammetry efforts within 60 km of Pt. Barrow. During these activities we remained at least 10 km from the traditional whaling sites. We also avoided overflying the whale census area, although ice conditions prevented an effective ice-based census in May 1989.

Ice Conditions

General

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 (Fig. 1).

The landfast ice forms gradually in fall and by late winter extends from 25 to 75 km offshore, depending on the position along the coast. During the initial phases of freeze-up, multiyear ice floes become grounded as they enter the nearshore region. As freezing continues, new ice locks these multiyear floes in place. These grounded multiyear floes, in turn, act to anchor new ice, contributing to its stability and shorefast tendency during spring breakup.

The pack ice is composed of floes of multiyear ice that are consolidated and supplemented by each year's annual ice. Multiyear ice in the Beaufort Sea averages 4 m in thickness and new ice can grow to 2.4 m in thickness during one winter season. Circulation patterns tend to move the pack westward along the Alaskan coast. This circulation is largely wind driven, and is less energetic in winter. During periods of westerly winds, the direction of ice drift can be reversed temporarily, becoming eastward.

Between the fast ice and the pack ice lies the shear zone. In this area pressure ridges form where shearing and compressive forces are exerted by the mobile pack ice on the less mobile pack ice and the fast ice. Pressure ridges may exceed 10 m in height (Tucker et al. 1984; Kovacs and Mellor 1974).

Marko and Fraker (1981) presented an idealized representation of spring ice cover in the Beaufort Sea showing typical locations of major leads (Fig. 1). The lead along the E-W offshore shear zone is an extension of the NW Alaska Lead, although the shear zone typically deviates 5-10° to the south at a point about 35 km east of Pt. Barrow. Marko and Fraker (1981) note that the lead along this shear zone does not coincide with the edge of the landfast ice at points more than about 35 km east of Pt. Barrow. Instead, it is situated well offshore amidst the pack ice. The E-W offshore shear zone is apparently the result of the shearing of the relatively mobile "Offshore Pack Ice" against the more stable "Close Ice" zone (Fig. 1).

Although the E-W offshore shear zone is the predominant area of lead formation in the Alaskan Beaufort Sea, leads also develop closer to shore, along or near the landfast ice edge that parallels the NE coast of Alaska. In general, this ice-edge is oriented WNW-ESE, and parallels the Alaskan coast from a point northeast of Pt. Barrow to the Mackenzie Delta. Based on the locations shown by Marko and Fraker (1981) for mid May, the fast-ice edge is ~25-55 km off the coast between Pt. Barrow and Cape Halkett in different years. The lead along this fast ice edge is the "Nearshore Flaw" shown in Figure 1.

The maps presented by Marko and Fraker (1981) for 20 April-10 June show that, in most years, there are periods when leads are present in our study area either in the E-W offshore shear zone or in both the shear zone and along the fast ice edge. Of the 8 years considered (1973-80), 1979 was the only year when leads were noticed only along the fast-ice edge. In 31 maps of ice features during various years and periods, there was a nearshore lead along the fast-ice edge in 13 cases (42%) and offshore leads in 29 cases (94%).

Marko and Fraker (1981) noted that few leads form in the Close Ice Zone (Fig. 1), and those that do form often subsequently close. This occurs because the prevailing easterly winds that tend to form leads elsewhere in the Beaufort Sea force the ice of the southwestern Beaufort Sea against the Alaskan coast, tending to consolidate it. Burns et al. (1980) found that leads were present in this zone only 26 to 43% of the time during the January to May period.

Lead locations and configurations can change markedly during a season (Marko and Fraker 1981). For example on 6 May 1978 there was a well developed lead east of Pt. Barrow in the E-W offshore shear zone (Fig. 7A). On 16 May this major lead was no longer evident and only some small leads well north of the 10 May lead location were present. The nearest open water north of Cape Halkett was about 100 km offshore on this date. By 30 May a major lead that extended from Pt. Barrow all the way into Amundsen Gulf was present in the E-W offshore shear zone. At this time the lead was within about 65 km of Cape Halkett. The data also show rapid shifts in lead positions between the E-W offshore shear zone and the fast ice edge, and lead configurations that were intermediate between the two "typical" locations.

Thus, leads in the southwestern Beaufort Sea tend to form offshore in the E-W offshore shear zone amidst the pack ice, and nearshore along the edge of the landfast ice. Because these two typical lead configurations form an acute angle with an apex east of Pt. Barrow, there is usually a lead in that area regardless of which lead configuration (offshore or nearshore) develops.

Farther east of Pt. Barrow, leads are also common in the E-W offshore shear zone. However, the maps presented by Marko and Fraker (1981) indicate that locations of leads within this zone vary considerably among and within years. The ice in this area is less stable than that near Pt. Barrow. Nearshore leads are uncommon along the fast ice edge off eastern Alaska, and those that do form are often short-lived. Thus, the area just east of Pt. Barrow is more favorable for the present study than is the area farther east.

1989 Ice Conditions

Ice conditions in 1989 were more closed than in the typical years described above.

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

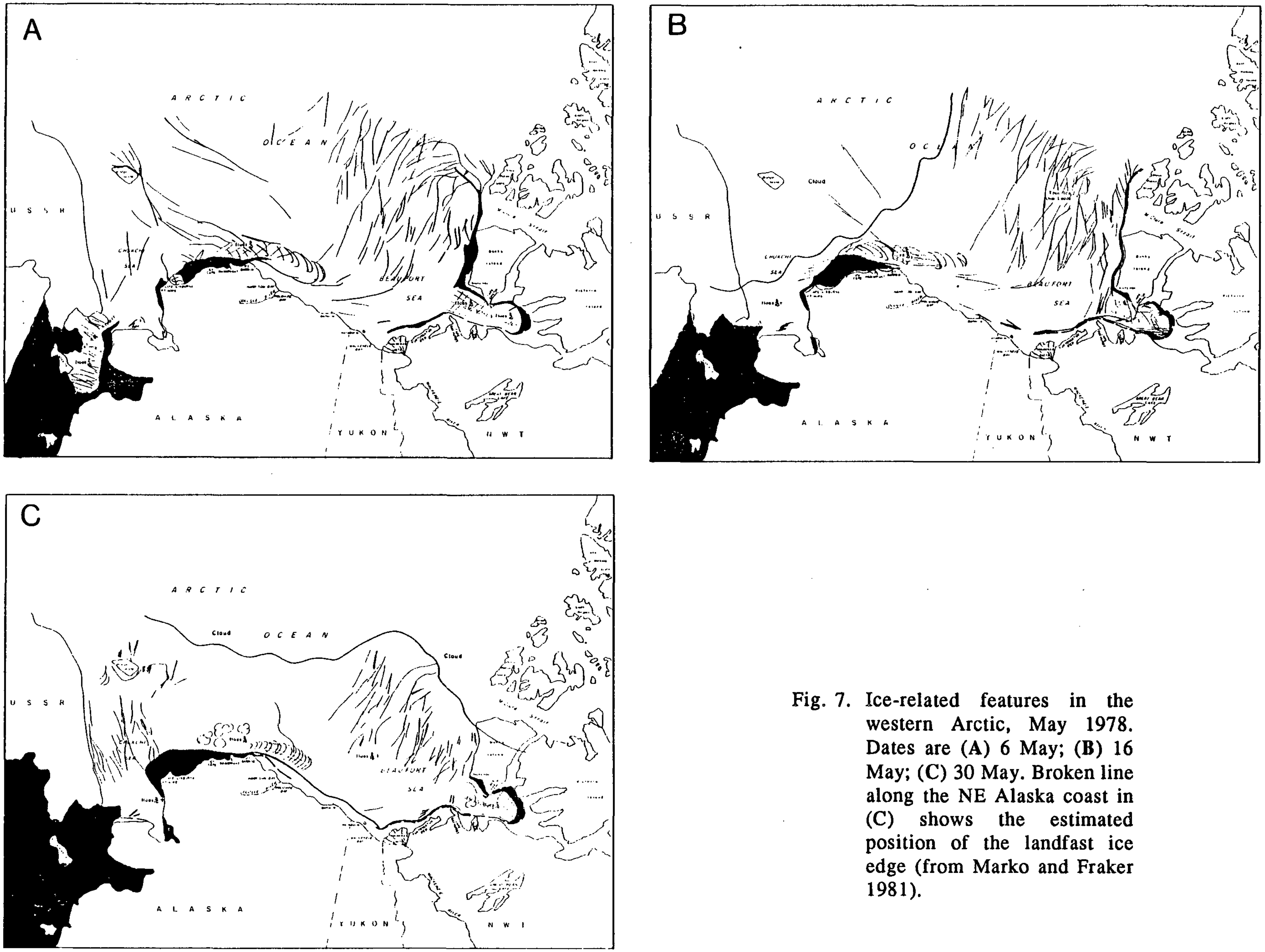

Fig. 7. Ice-related features in the western Arctic, May 1978. Dates are (A) 6 May; (B) 16 May; (C) 30 May. Broken line along the NE Alaska coast in (C) shows the estimated position of the landfast ice edge (from Marko and Fraker 1981).

consisted of small holes among pans plus narrow cracks and leads that tended to be oriented NW to SE. These conditions were maintained until 7 May. Minor shifts in the pack ice formed small holes, cracks and small leads at about the same rate as older ones were freezing. The amount of open water or thin newly-refrozen ice decreased as one went east from Pt. Barrow. In the area 60 km or more to the NE, ENE and E, there were no extensive leads or open areas, and indeed very little open water in any configuration. From 7 to 11 May slightly colder temperatures (-6 to -23°C offshore) and calm winds resulted in freezing of virtually all open water in the study area (Plate 1).

On 12 May moderate NNE winds (26 km/h) shifted the offshore pack ice and formed several minor leads oriented SW to NE. The overall ice cover recorded during the aerial survey on that date had decreased to 95%. Moderate NE winds continued for the next few days and the NW Alaska Lead finally developed along the fast ice edge as far north as several kilometers to the northeast of Barrow. However, this lead was farther offshore than usual and a broad shelf of rough, rubble ice between the stable landfast ice and the lead made access to the lead from Barrow almost impossible by snowmachine. Because of this, the ice-based whale census normally done by the North Slope Borough could not be conducted during our 1989 study period. In most years, the NW Alaska Lead is present off Barrow, at least intermittently, by mid-to-late April.

By 13 May no major leads had developed in our study area either along the fast ice edge or in the offshore shear zone, but the overall ice cover had decreased to 85%. The open water areas consisted of short leads up to 5 km in length and large irregular-shaped areas of open water amidst the pack ice. Although most of the short leads were oriented generally SW to NE, there was no well defined migration corridor for whales to follow.

On 15 May the wind decreased to 15 km/h and some of the open water areas began to freeze. On 16 May the wind was light (13 km/h) from the SW and the open water areas in the study area were further reduced to 5% by freezing and compression of the pack ice by the wind.

Ice conditions remained about the same until 20 May when the ice started to open up. The lead along the fast ice edge extended well east of Pt. Barrow for the first time, and ice cover in the study area decreased to 90%. Strong winds on 21 May further loosened the pack ice in the study area to 80% ice cover, and a lead 1-6 km wide developed along the landfast ice edge as far east as 60 km east of Pt. Barrow. This was a northeastward and eastward extension of the NW Alaska lead. The ice cover north of the lead was 90%; this pack ice contained open water areas having irregular shapes and no particular orientation.

From 22 to 29 May there were no major changes in ice conditions. The lead along the landfast ice edge widened slightly and extended farther east, to 85 km east of Pt. Barrow (Plate 2). However, no notable changes occurred in the pack ice north of the lead.

On 30 May the pack ice moved south and partially blocked the nearshore lead west of 155°30′ and east of 154°30′. The 35 km stretch of lead between these longitudes had widened. On that date, the last day of our field season, open water areas among the pack ice north of the lead had also expanded.

Specific information on ice conditions near each experimental site appears in the "Bowhead Results - Reactions to Playbacks" section. For each experiment, that section maps and describes the ice near the sound projector and the whales.

Weather

General

As part of the planning process, spring weather data from northern Alaska were reviewed. Weather was expected to have strong influences on project logistics and the feasibility of various field procedures. Weather data have not been collected systematically within our offshore study area. However, systematic data have been reported for May from two coastal stations near the study area (Barrow, 1948-74 period, and Lonely DEW site, 1957-75). Opportunistic weather observations in marine areas to the north and west of Barrow have also been summarized for May of 1872-1974 (Fig. 8; Brower et al. 1977).

The mean temperatures recorded in May at Barrow, Lonely and marine areas NW of Barrow were -7, -6.5 and -10.5°C. Temperatures appear to have been related only weakly to wind direction, but tended to be 2-4 C° warmer when winds were out of the S, SW or W (Fig. 9).

The predominant winds at all locations during May were out of the E and NE. At the two coastal stations, winds from the E or NE sectors occurred over 50% of the time during May. In the offshore area, these winds occurred over 40% of the time (Fig. 10). The mean wind speeds at Barrow, Lonely and offshore were, respectively, 18.7 km/h (10.1 knots), 14.8 km/h (8.0), and 19.2 km/h (10.4). The wind direction did not change with time of day at the two coastal sites, but there was a tendency for slightly lower wind speeds during the early morning (00:00 to 08:00 h) except at Lonely (Fig. 11, 12).

Precipitation was recorded at 37% of the May observation times at Barrow, 9% at Lonely and 25% offshore (Fig. 13). Most of this precipitation was in the form of snow.

Visibility and ceiling have direct influences on the feasibility of the aircraft operations necessary for the project. Horizontal visibility during May is surprisingly good according to Brower et al. (1977). Visibility was ≥9.3 km (5 n.mi.) about 70% of the time. The ceiling was ≥610 m (2000 ft) only ~34% of the time at Barrow, but it was 305-610 m an additional ~22% of the time[2].

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[2] Actual percentages may be as much as 4% higher, given the manner in which Brower et al. (1977) present the data.

Plate 1. NOAA Satellite imagery taken on 8 May 1989 showing the extensive offshore ice cover near Barrow, Alaska.

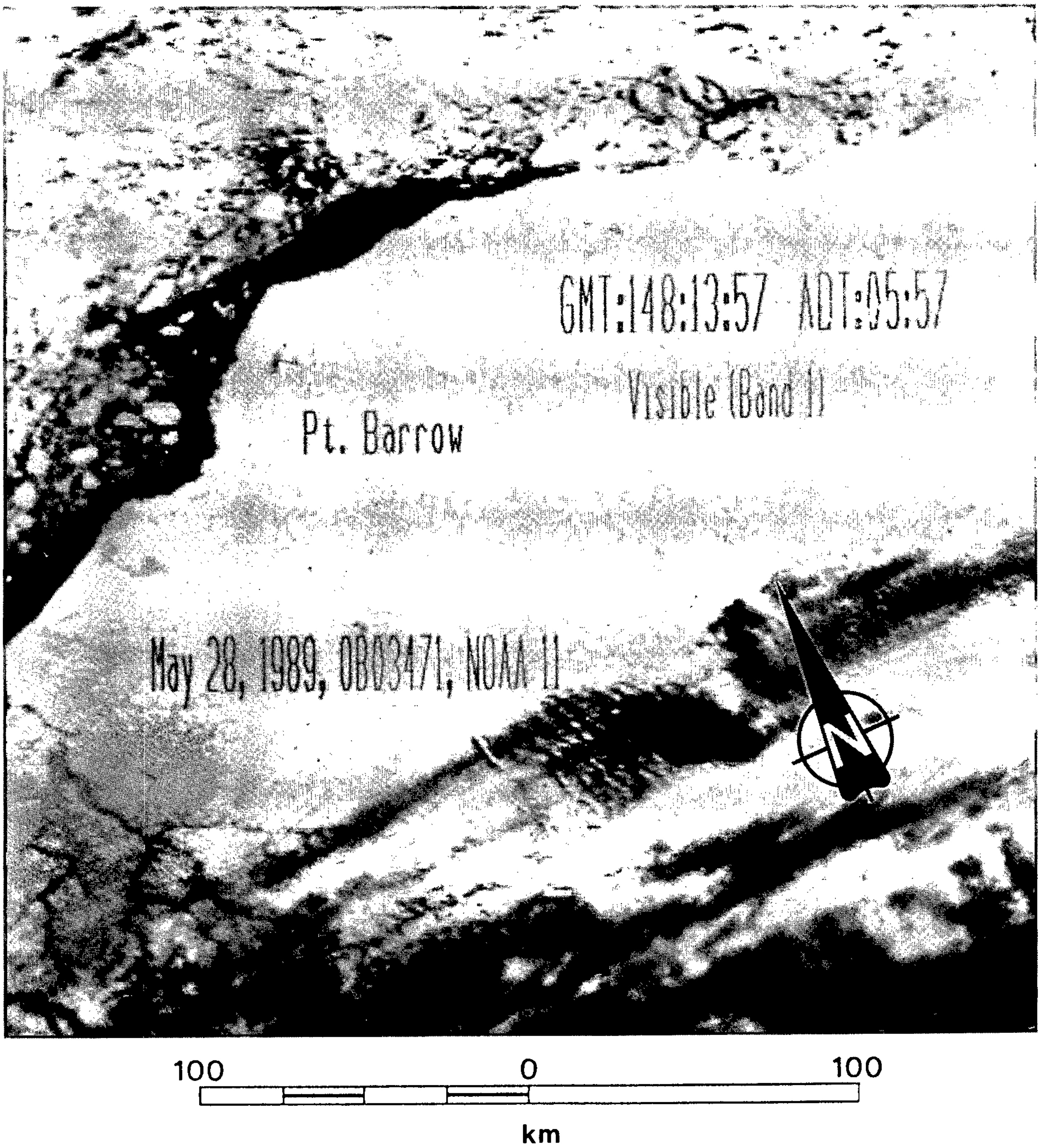


Plate 2. NOAA Satellite imagery taken on 28 May 1989 showing the NW Alaska lead and the extensive offshore ice cover near Barrow, Alaska.

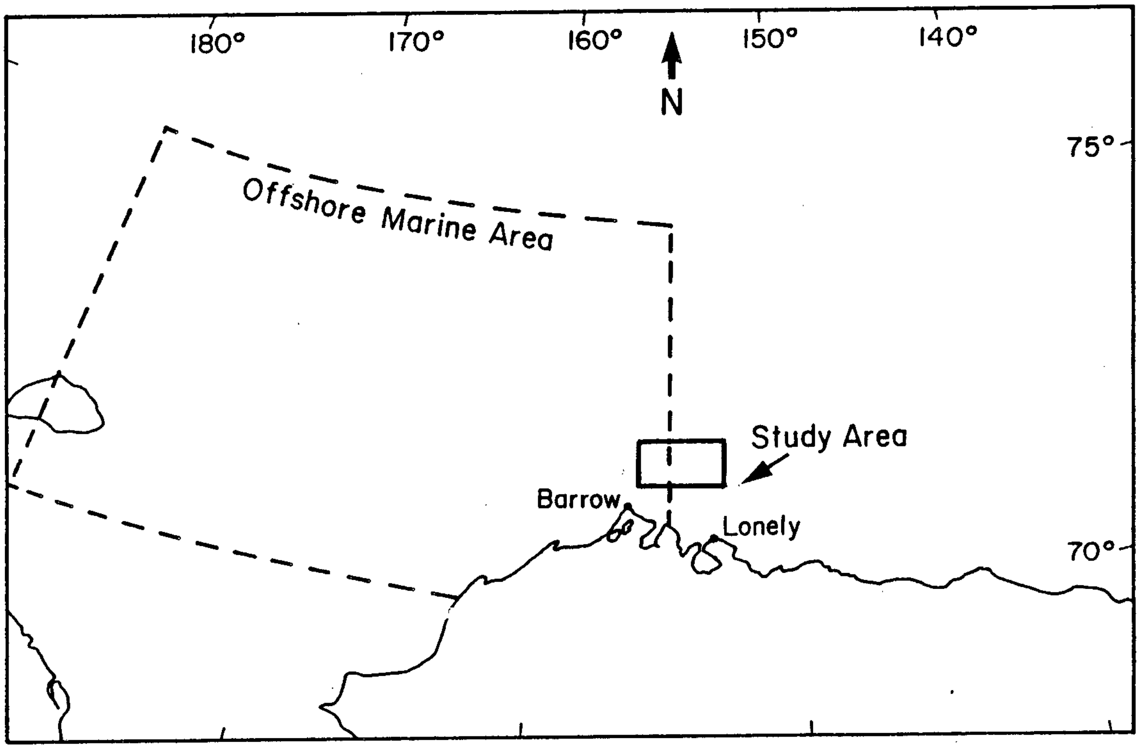


Fig. 8. Sources of weather information near the study area as summarized from Brower et al. (1977).

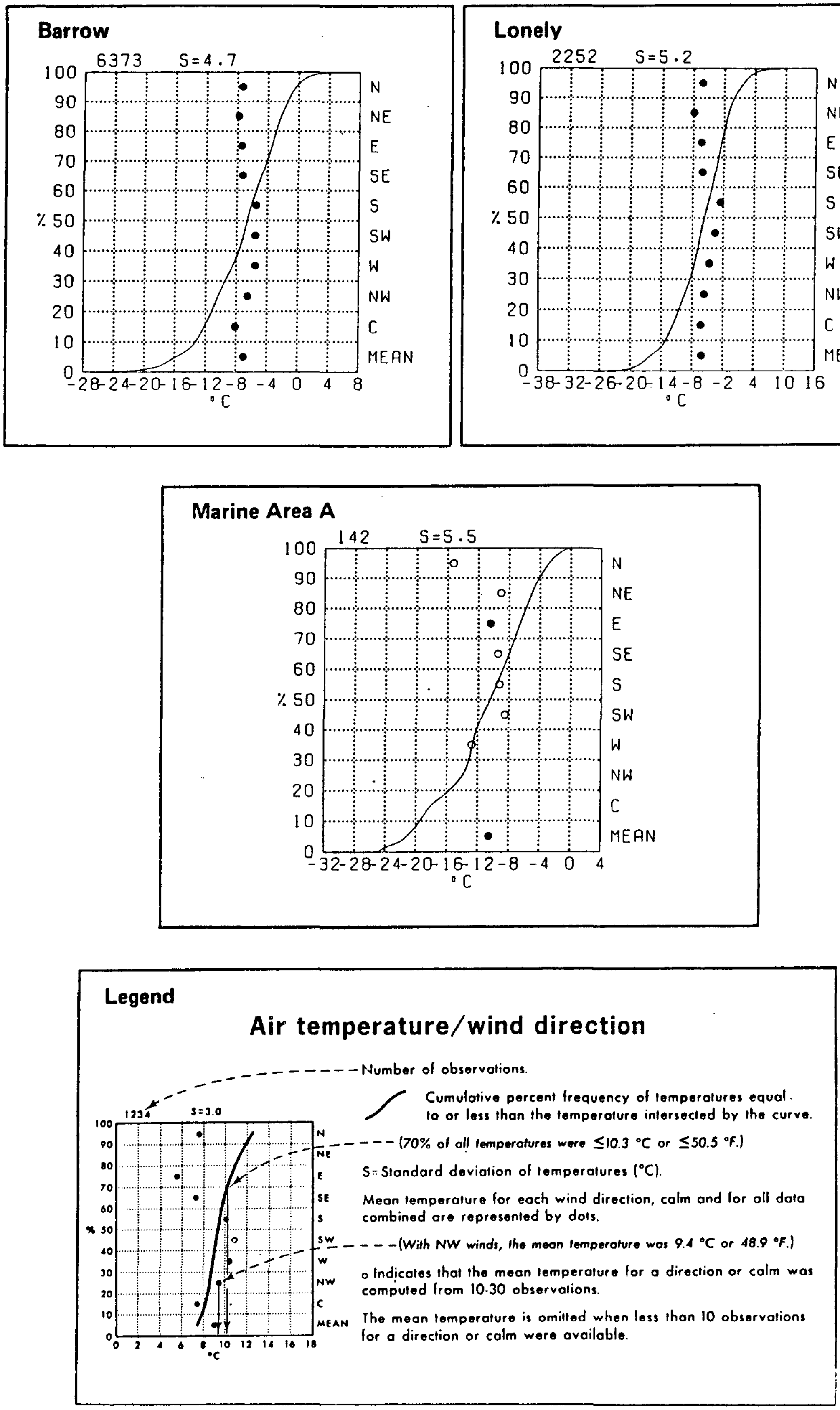


Fig. 9. Air temperature in relation to wind direction at selected locations near the study area in May (from Brower et al. 1977). Data for Barrow and Lonely are from 1948-1974 and 1957-1975, respectively, and data for offshore areas are from 1872-1974.

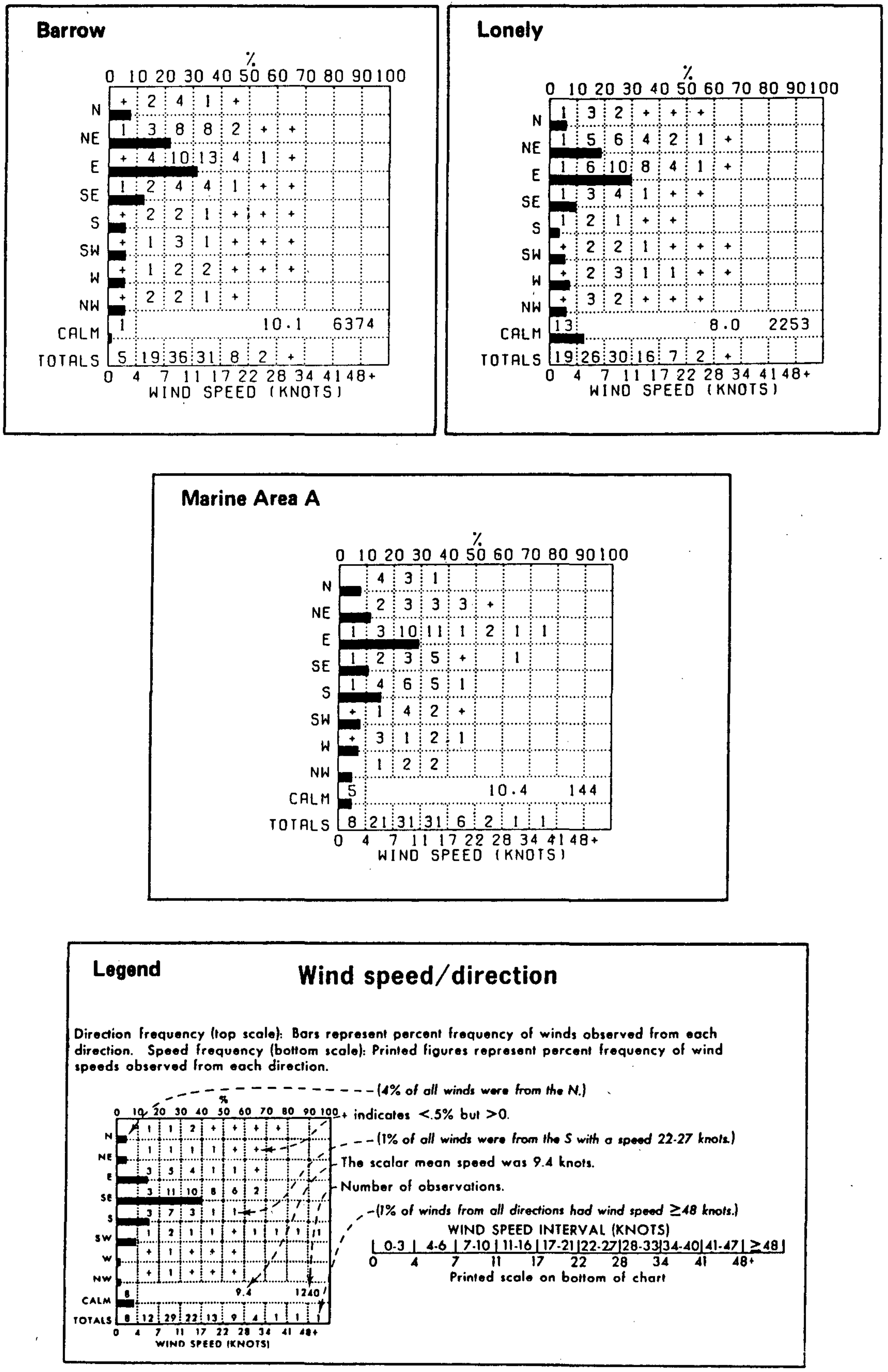


Fig. 10. Wind speed in relation to wind direction at selected locations near the study area in May (from Brower et al. 1977). Data for Barrow and Lonely are from 1948-1974 and 1957-1975, respectively, and data for offshore areas are from 1872-1974.

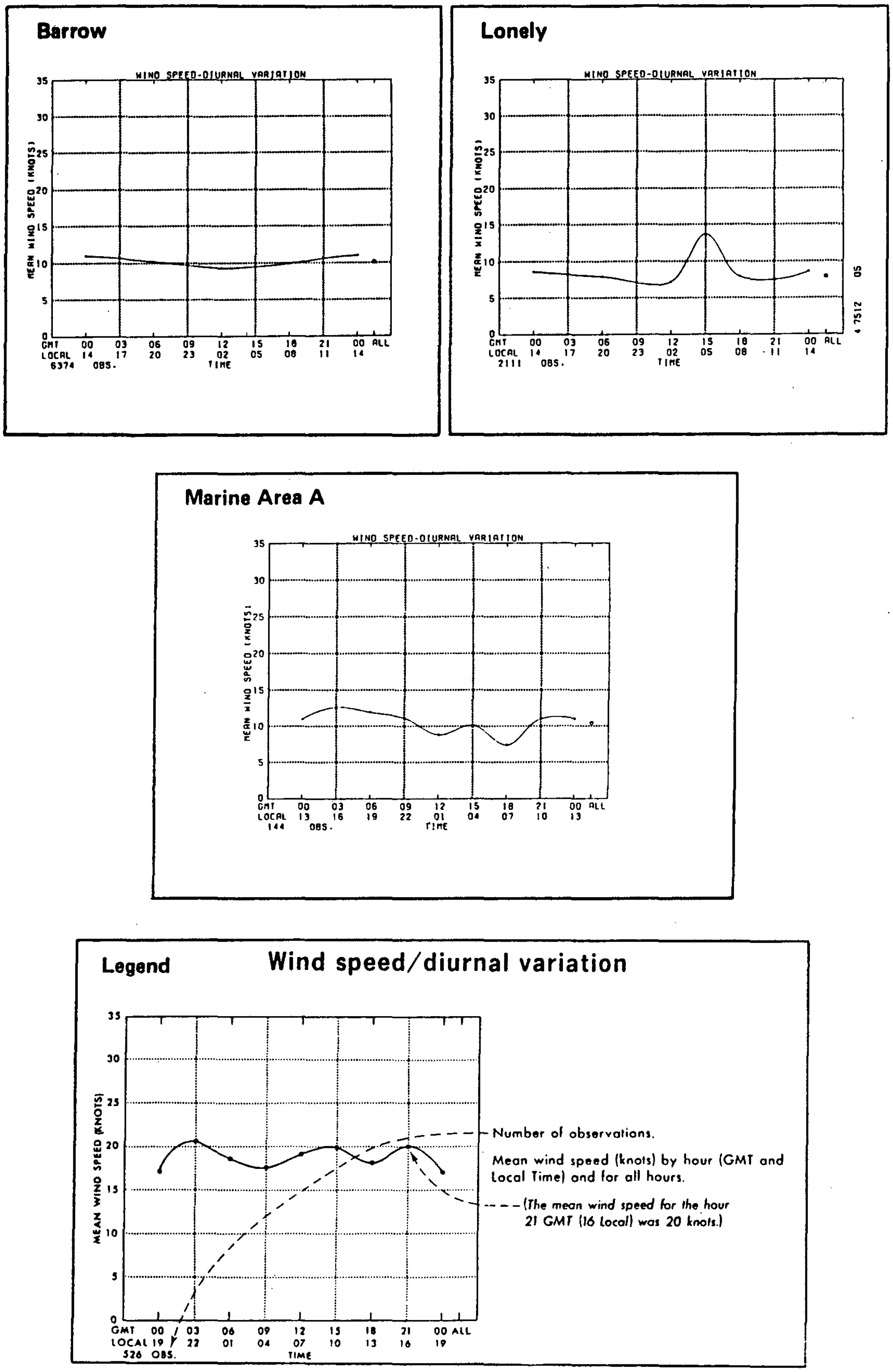


Fig. 11. Wind speed in relation to time of day at selected locations near the study area in May (from Brower et al. 1977). Data for Barrow and Lonely are from 1948-1974 and 1957-1975, respectively, and data for offshore areas are from 1872-1974.

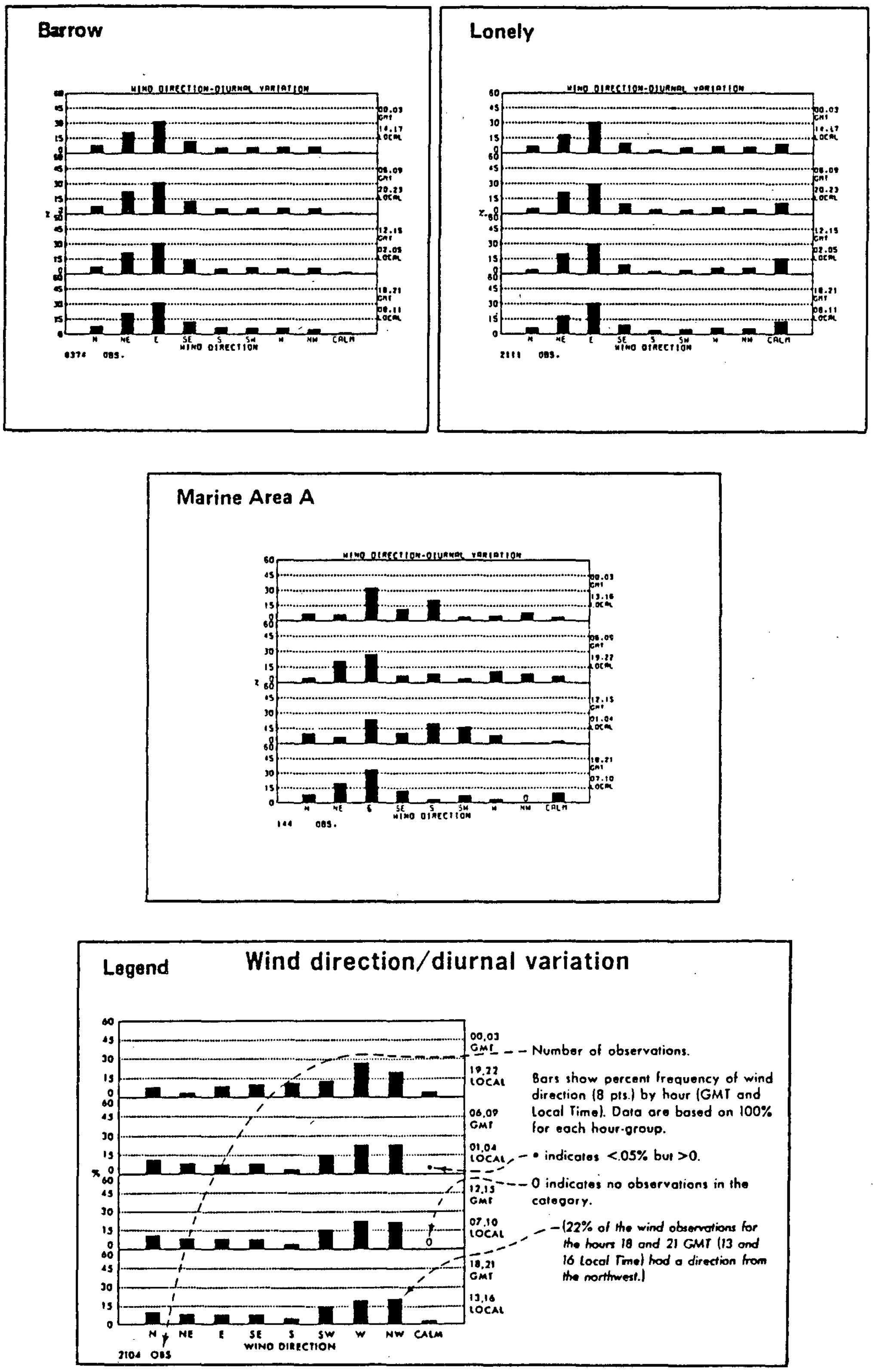


Fig. 12. Wind direction in relation to time of day at selected locations near the study area in May (from Brower et al. 1977). Data for Barrow and Lonely are from 1948-1974 and 1957-1975, respectively, and data for offshore areas are from 1872-1974.

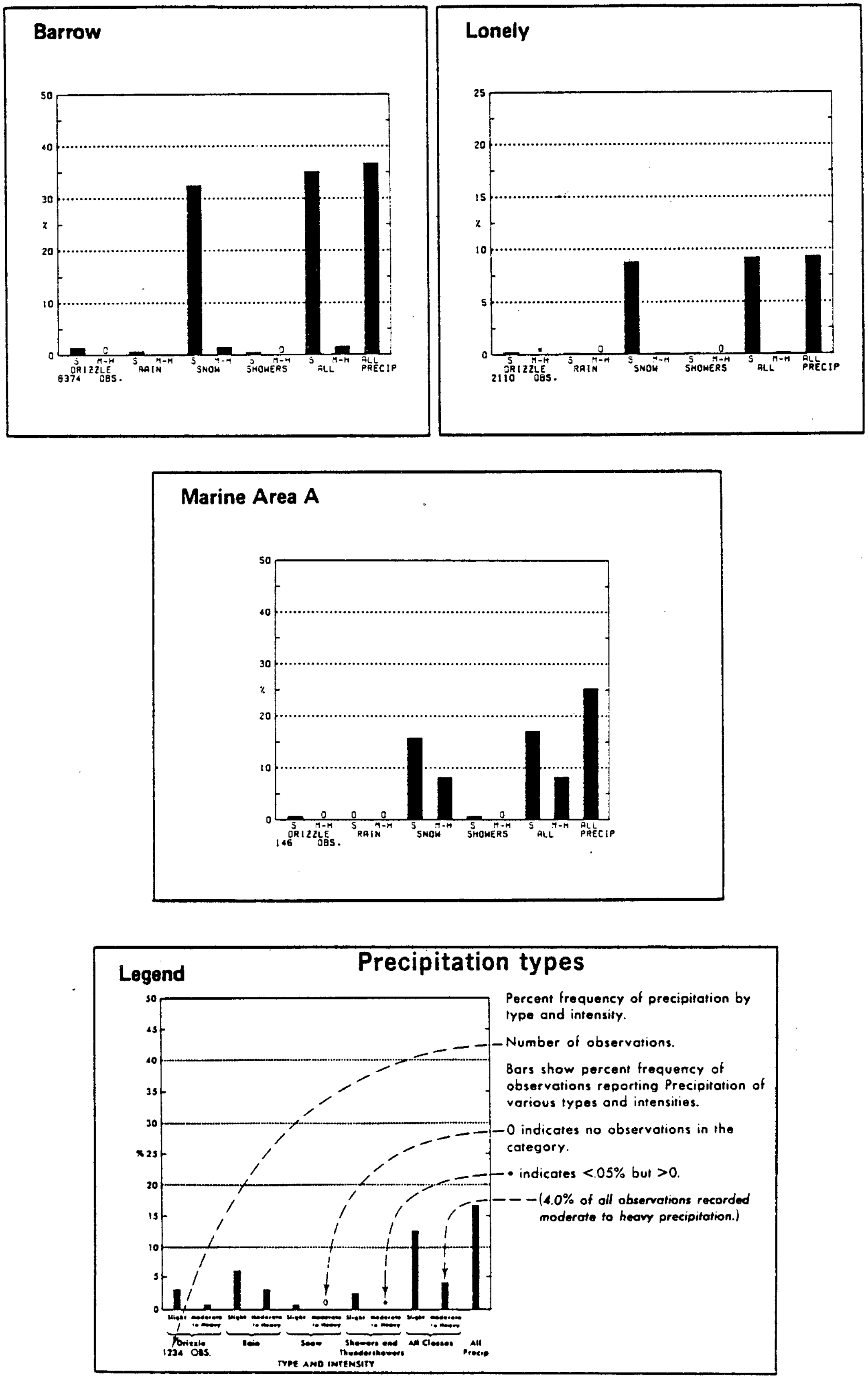


Fig. 13. Frequency of precipitation of various types at selected locations near the study area in May (from Brower et al. 1977). Data for Barrow and Lonely are from 1948-1974 and 1957-1975, respectively, and data for offshore areas are from 1872-1974.

In offshore areas the reported ceiling tended to be much higher: ≥610 m 60% of the time and ≥305 m a full 79% of the time (Fig. 14). It should be noted that the accuracy of ceiling data is variable; some observations may be based on visual estimates of dubious reliability.

Fog was relatively infrequent during May (Fig. 15). Overall, it was reported only 12% of the time at Barrow and 18% of the time at Lonely. As expected, fog was most common during the early morning (18% of the time at Barrow during the 02:00-05:00 period) and rare during the afternoon (7% of the time at Barrow during the 14:00-17:00 period). Fog tended to be most common during periods of calm, E and SE winds.

1988 Weather

Additional weather data were provided by the North Slope Borough's Department of Wildlife Management, which recorded weather data by 2-h periods during their 1988 ice-based whale census near Barrow. Table 1 summarizes their cloud information for 1988.

Table 1. Proportion of days having clear (upper) or clear and partially cloudy (lower) weather near Barrow during the 1988 census period. Data provided by J.C. George, Dept of Wildlife Management, North Slope Borough, Barrow, AK.

	Clear ≥ 6 h	Clear < 6 h	No Clear Periods
26-30 April	0.33	0.00	0.67
1-15 May	0.53	0.20	0.27
16-31 May	0.06	0.00	0.94
1-10 June	0.67	0.00	0.33
26 April-10 June	0.35	0.08	0.58
	Clear or Partially Cloudy ≥ 6 h	**Clear or Partially Cloudy < 6 h**	**No Clear or Partially Cloudy Periods**
26-30 April	0.75	0.00	0.25
1-15 May	0.80	0.00	0.20
16-31 May	0.19	0.06	0.75
1-10 June	0.83	0.00	0.17
26 April-10 June	0.56	0.02	0.41

Behavioral observations would have been possible from an aircraft circling above whales during all periods with clear skies and most periods with partly cloudy skies. In addition, observations could be conducted during an unknown portion of cloudy periods, i.e. those when the ceiling was >460 m ASL. Based on the 1988 data, extended periods of observation from an aircraft would have

Barrow

VISIBILITY

LOW CLOUD CEILING	<1/2	1/2<1	1<2	2<5	5<10	≥10
NC	1	+	+	1	16	6
50<80	+	+	+	+	1	1
35<50	+	0	0	+	1	+
20<35	+	+	+	1	5	1
10<20	+	1	1	4	15	1
6<10	+	1	1	4	16	1
3<6	1	1	1	3	6	+
1.5<3	+	+	+	+	+	0
0<1.5	4	1	+	+	+	+

6365

Lonely

VISIBILITY

LOW CLOUD CEILING	<1/2	1/2<1	1<2	2<5	5<10	≥10
NC	1	1	+	1	9	14
50<80	+	0	0	0	1	1
35<50	0	0	0	0	+	+
20<35	+	+	+	1	4	4
10<20	1	2	2	4	22	7
6<10	1	2	2	2	6	1
3<6	1	1	1	1	2	+
1.5<3	+	+	+	+	+	0
0<1.5	3	+	+	+	0	0

2245

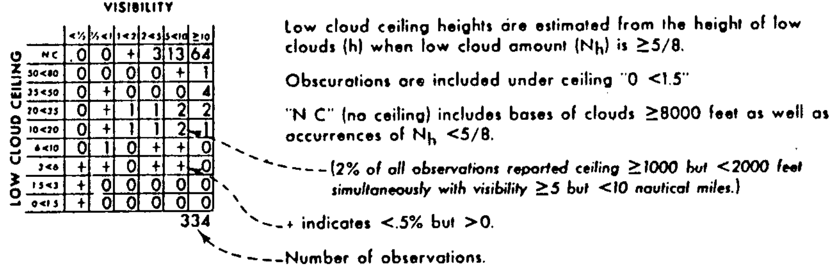
Marine Area A

VISIBILITY

LOW CLOUD CEILING	<1/2	1/2<1	1<2	2<5	5<10	≥10
NC	1	0	0	1	13	28
50<80	1	0	0	0	0	2
35<50	0	0	0	1	1	1
20<35	1	0	1	1	3	5
10<20	0	1	1	1	15	1
6<10	2	0	1	2	3	0
3<6	2	1	1	2	1	0
1.5<3	0	1	1	0	0	0
0<1.5	5	0	0	0	0	0

143

Legend **Low cloud ceiling/visibility**



VISIBILITY

LOW CLOUD CEILING	<1/2	1/2<1	1<2	2<5	5<10	≥10
NC	0	0	+	3	13	64
50<80	0	0	0	0	+	1
35<50	0	+	0	0	0	4
20<35	0	+	1	1	2	2
10<20	0	+	1	1	2	1
6<10	0	1	0	+	+	0
3<6	+	+	0	+	+	0
1.5<3	+	0	0	0	0	0
0<1.5	+	0	0	0	0	0

334

Percent frequency of simultaneous occurrence of specified low cloud ceilings (hundreds of feet) and visibilities (nautical miles).

Low cloud ceiling heights are estimated from the height of low clouds (h) when low cloud amount (N_h) is ≥5/8.

Obscurations are included under ceiling "0 <1.5"

"N C" (no ceiling) includes bases of clouds ≥8000 feet as well as occurrences of N_h <5/8.

(2% of all observations reported ceiling ≥1000 but <2000 feet simultaneously with visibility ≥5 but <10 nautical miles.)

+ indicates <.5% but >0.

Number of observations.

Fig. 14. Low cloud cover and horizontal visibility at selected locations near the study area in May (from Brower et al. 1977). Data for Barrow and Lonely are from 1948-1974 and 1957-1975, respectively, and data for offshore areas are from 1872-1974.

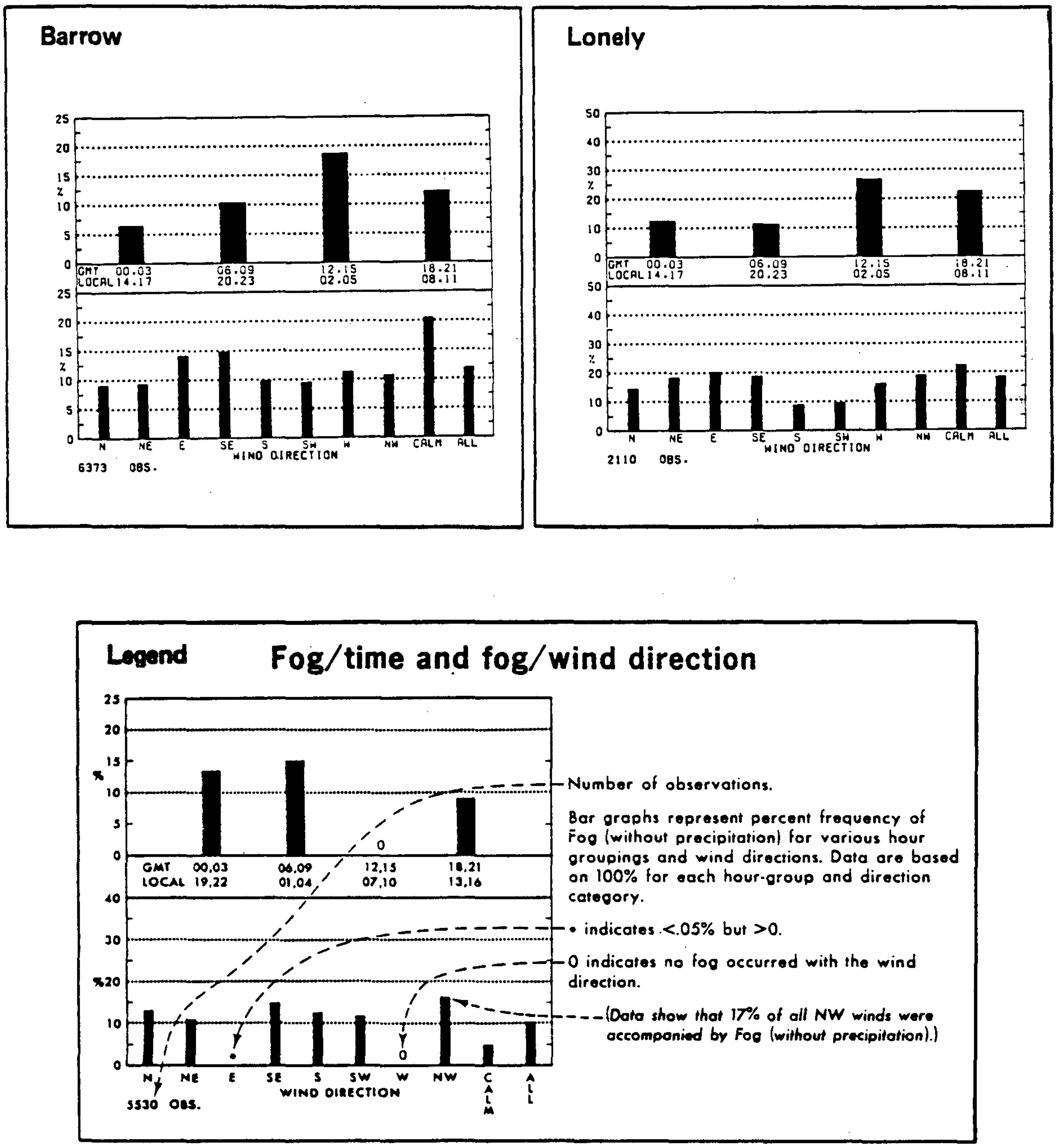


Fig. 15. Fog in relation to time of day and wind direction at selected locations near the study area in May (from Brower et al. 1977). Data for Barrow and Lonely are from 1948-1974 and 1957-1975, respectively; few data were obtained for offshore areas.

been possible during at least 35% of the days (Table 1). Brief periods of observation would have been possible on at least 43% of the days (0.35 + 0.08), and probably on at least 58% of the days (0.56 + 0.02). Additional observations probably would have been possible on some cloudy days--those when the ceiling was >460 m.

It appears that, in the spring of 1988, behavioral observations could have been conducted from an aircraft circling at 457 m ASL for parts of at least 60% of the days. This was so even though the spring of 1988 was a season with extensive open water, which would tend to cause fog and low cloud.

1989 Weather

We did not record weather conditions systematically during this study, but weather was recorded at the ice camp when it was set up on the pack ice, and at Barrow on a non-systematic basis.

The winds were from the WSW and SW during the last few days of April and first three days of May. This moved the pack ice in the northern Chukchi Sea northeastward. The closed ice conditions that resulted prevented formation of the NW Alaska lead southwest of Barrow. Except for periods of fog during the morning, skies were clear and weather conditions were suitable for observing whales had more open water been present.

From 5 to 8 May, the temperature was cold (lows of about -20 to -30°C) and the few open water areas amidst the offshore pack ice froze. During this period, winds were light and from the E to NE. Ceilings improved from low overcast on 4-6 May to partially cloudy and clear on 7 and 8 May. On 9 May, the temperature rose to -6°C in offshore areas, winds were light, and the sky was partly overcast--ideal conditions for observing whales. However, there was virtually no open water.

Weather conditions were poor during the 10-13 May period. Ceilings were low (<335 m) and visibility was poor in snow and fog. Winds were out of the NE quadrant but were light to moderate (<25 km/h). Consequently, some leads formed amidst the offshore pack ice.

The ceiling lifted temporarily to >460 m during the morning and early afternoon of 14 May. The temperature was warm (-7°C) and the winds were moderate (23-27 km/h) out of the NE.

The temperature, ceilings and visibility decreased on 15 May with snow flurries occurring throughout most of the day. Similar weather continued until 20 May. Ceilings varied between 150 and 460 m (occasionally to 670 m); winds were light to moderate, primarily from the NE sector; temperatures were -2 to -7°C and light snow and snow squalls were present much of the time.

The winds increased to 24-41 km/h on 20 and 21 May and the upper cloud layers thinned out. Fog and blowing snow reduced visibility to 1-9 km. The strong winds from the NE to SE started to open a lead along the fast ice edge north and NE of Barrow.

Low ceilings and poor visibility due to snow and fog persisted throughout 22 May and the morning of 23 May. Conditions improved on the afternoon of 23 May; winds were 19-26 km/h from the NE to SE, ceilings were 365-460 m and the temperature offshore was -2 to 4°C.

Low ceilings (with freezing rain on the morning of 24 May) and variable visibility persisted from 24 to 26 May. Winds were light from the SE and temperatures were -2 to 4°C.

The weather cleared early on 27 May and remained clear for the rest of the study. Winds were light from the S (27 May) and E (28 and 29 May), and air temperatures were +1 to +7°C. Ceilings were usually unlimited with occasional partially overcast periods.

In **summary**, weather and ice conditions in 1989 were worse than normal for conducting bowhead whale studies. Weather was clear at the end of April and early May, but little open water was present. Unusually cold weather from 5 to 8 May froze existing open water areas and consolidated the offshore pack ice. From 10 to 26 May, low ceilings, snow and fog prevented aerial observations from >460 m ASL most of the time. Observing conditions were ideal on 27-30 May, but most bowheads had migrated past Barrow by this time.

METHODS

Acoustical Field Methods

Industrial Noise

Specific objective 1 was to record and characterize the underwater noise from a drilling operation on a grounded ice pad in shallow water during late winter. 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*). The site was at 70°19.5'N, 147°30.3'W, 8.1 km south of Narwhal Island (in the McClure Islands) and 38.7 km ENE of the Deadhorse airport at Prudhoe Bay. A drillrig was installed on an ice platform about 150 m in diameter. It had been built by spraying sea water into the air to form ice granules. In this construction method, the layer of ice formed by these granules gradually thickens until it rests on the bottom. The rig used a conventional rotary table and kelly to drive the drillstring. Recordings were made at six distances, ranging from 0.13 to 5 km, along each of two bearings from the drillrig: southeast and northwest. At each receiving station, a hole was drilled through the landfast ice and an ITC model 6050C hydrophone was lowered to mid-depth. Water depth was 6-7 m, ice thickness was close to 2 m, the wind was light, and the air temperature ranged from -25° to -17°C. Chevron U.S.A. provided full support in permitting us to make the sound recordings at *Karluk*. They also provided the drilling operation logs to permit us to determine the rig activity at the recording times.

Underwater sounds from a Bell 212 helicopter and a deHavilland DHC-6-300 Twin Otter were recorded by having the aircraft fly over a pair of ITC 6050C hydrophones suspended over the edge of an ice floe via faired cables. Both of these aircraft are powered by twin Pratt & Whitney Canada PT6 turbine engines: the Bell 212 by the PT6-T turboshaft and the Twin Otter by the PT6A-27 turboprop. Hydrophone depths were 3 and 18 m. The helicopter flyover sounds were recorded on 17 and 28 May; the Twin Otter sounds were recorded only on 28 May. For each aircraft and date, at least two passes were made (in opposite directions) at each of four altitudes. On 17 May, altitudes were 76, 152, 305 and 457 m (250-1500 ft). On 28 May, altitudes were 76, 152, 305 and 610 m (250-2000 ft) for the helicopter and 152, 305, 457 and 610 m (500-2000 ft) for the Twin Otter. The passes were oriented perpendicular to the ice edge along which the hydrophones were deployed. Helicopter passes were made at normal cruise speed (185 km/h). Twin Otter passes were made both at normal cruise speed (285 km/h) and at a lower power setting (185 km/h).

Sound Propagation

Specific objective 3 was to measure and model transmission loss of underwater sound. Sound propagation tests, also called sound Transmission Loss (TL) tests, were conducted on five dates: 29 and 30 April, and 2, 9 and 25 May 1989. Each test was conducted from a base camp on the pack ice at which a U.S. Navy J-11 sound projector was installed. The locations are shown as the five squares on Fig. 19, in the "1989 Chronology" section, p. 72. The projector was suspended from the edge of an ice pan at a depth of 9 m for TL tests 1 and 2, and 18 m for tests 3-5. Power was supplied 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 three types of sounds to be projected: tonal sweeps, pure tones, and sounds from the drillrig at *Karluk*. ▶ The tonal sweeps were special "hyperbolic frequency modulation" (HFM) signals synthesized by BBN (Rihaczek 1986). Each 5-s sweep spanned one-third octave at a center frequency of 100, 200, 500, 1000, 2000, or 5000 Hz. Each sweep was sent twice (TL tests 1-2) or four times (tests 3-5) with no pauses between sweeps. ▶ The pure tones were at 50, 100, 200, 500, 1000, 2000, 5000, and 10,000 Hz. Each tone was transmitted for 10 s (TL tests 1-2) or 20 s (tests 3-5), with 5 s between tones. ▶ The *Karluk* sounds were a 37-s (or longer) segment from the recording made 130 m away from the *Karluk* drillsite. The operator rewound the tape after each transmission ended.

The sound projected by the J-11 was monitored with an ITC model 1042 spherical hydrophone placed at a nominal distance of 0.8 m in front of the projector face. The actual distance was measured during each installation, and a correction term of 20 log (distance) was applied to the measured sound level to compute the source level at 1 m. The waveform from the monitor hydrophone was displayed on an oscilloscope to ensure that the projector was not overdriven to the point of distortion. The source level of the projector depended on the frequency content of the signal, but was typically near 165 dB re 1 μPa at 1 m.

The receiving/recording equipment consisted of an ITC model 6050C hydrophone, a 0-60 dB selectable gain postamplifier, and a Sony TC-D5M cassette recorder. The receiving station crew used a Rolotape distance measuring wheel to locate receiving sites at ranges 100, 200, and 400 m (if possible) along the edge of the ice pan. At each distance, the hydrophone was lowered on a faired cable to 18 m depth, and a recording of the ambient noise was made. The recording crew then radioed the base camp to request transmission of the taped signal. When transmissions ended, ambient noise was recorded again. During some tests, ambient noise was recorded at ranges 100-400 m with the generator at the base camp turned off as well as operating. This was done to determine the characteristics and range of detectability of the generator sounds.

More 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 10 n.mi. (0.9-18.5 km). Suitable sites were those along the edge of an ice pan 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, but 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[3]. When beyond radio range, the base camp operator played the tape at prescribed times, generally at 10-min intervals commencing on the hour. The remote recording crew then knew when the signals were being transmitted even if the signals could not be heard.

About 4 h were required to measure received signals at eight ranges from 100 m to 18.5 km, exclusive of the time (4-5 h) needed to set up and remove the projection equipment.

Acoustical Monitoring During Playbacks

Manually-deployed Sonobuoys.--Prior to each drilling noise playback test, a sonobuoy was installed manually at a nominal distance of 1 km from the projector. The helicopter was used for transportation to this site. On most occasions, we used a Sparton Defense Electronics AN/SSQ-41B wideband sonobuoy that had been modified to use external batteries for longer life. Also, its cutoff mechanism had been disabled so as 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 12 m. Both types of sonobuoys provide useful data from 10 to 20,000 Hz. These buoys telemeter the received sounds on VHF frequencies 162.25-173.5 MHz. The distance of the sonobuoy from the ice camp was determined roughly via the helicopter's GNS system as described in the previous section. On most days this was checked via theodolite, as described on p. 59-60.

A calibrated L-tronics model LS44 receiver was set up at the base camp to monitor the sounds received at this sonobuoy. The same telemetered 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, thus providing received level data at one known range (~1 km) in addition to the known level at the projector.

Air-dropped Sonobuoys.--Sonobuoys were dropped from the Twin Otter aircraft 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 buoys; they were standard naval sonobuoys except that the hydrophone deployed only to 12 m depth. The signals were received via an RF preamplifier and calibrated Regency MX5000 wideband FM receiver on the aircraft. These signals were recorded on a calibrated Marantz PMD430 cassette recorder for later analysis. Sometimes the presence of faint *Karluk* drilling sounds could be detected by spectrum analysis of these recordings even if they could not be distinguished by listening. (To the human ear, bearded seal calls often tended to obscure the drilling sounds.)

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[3] A homing beacon left at the ice camp provided increased assurance that the camp could be re-located even in poor visibility or if other navaids failed.

Ambient Noise

Specific objective 2 was to measure ambient noise. During the five transmission loss tests, ambient noise was recorded at each range station before and after the tones and other signals were received. These data were recorded with an ITC 6050C hydrophone at 18 m depth. Each of these ambient noise recordings was typically 2-4 min in duration.

Ambient noise also was recorded at the beginning and end of each playback experiment. Most of these data were telemetered from the wideband -41B or -57A sonobuoys that were deployed manually about 1 km from the ice camp, as described above. Recordings usually were 2-4 min in duration.

When -57A sonobuoys were air-dropped near whales, the signals were generally recorded aboard the aircraft from splash-down until the aircraft departed the area. During some of these periods the sound projector was inactive or too far away to be audible, and aircraft sound was detectable only a minority of the time. These sonobuoy recordings provided additional ambient noise data.

Acoustical Analysis Methods

Industrial and Ambient Noise

The basic tool for sound analysis was a computer workstation programmed for narrowband spectrum analysis and for third-octave and one-octave band level computation. The tape-recorded sounds were filtered (passband from 5 Hz up to slightly less than half the sample frequency) and amplified as necessary. These signals were sampled and digitized (12 bit resolution) in blocks, usually 8.5 s in duration. The sampling rate varied depending on the frequency band to be analyzed, extending from 2048 samples per second for 10-1000 Hz analysis to 32,770 samples/s for 10-16,000 Hz analysis. Spectrum analysis was by an FFT (Fast Fourier Transform) algorithm using block sizes of 2048-8192 samples, Blackman-Harris windowing, 50% overlap of blocks, and averaging of results from all blocks within the 8.5 s sampling period. The various combinations of sampling rate, frequency range, and effective analysis resolution were as follows:

Sample Rate	Anal. Freq. Range	Eff. Analysis Width
1024 Hz	10 - 500 Hz	1.7 Hz
2048	10 - 1000	1.7
4096	10 - 2000	1.7
8192	10 - 4000	1.7
16384	10 - 8000	1.7
32770	10 - 16000	3.4

The averaged spectra for the tape recorder outputs were referenced to volts squared per Hz. These "raw" spectra were converted to spectra referenced to $\mu Pa^2/Hz$ by applying calibration corrections for the tape recorder, sonobuoys and their receivers (if involved), preamplifiers, postamplifiers and hydrophones. These corrections were frequency dependent.

The acoustical powers in the analysis cells were added appropriately to compute third-octave band levels, one-octave levels, and the 20-1000 Hz broadband level. The frequencies and levels of peaks in the spectrum were printed to aid in identifying tonal components and harmonic families of tones. Results from each spectrum analysis were printed, plotted, and saved in a disk file for further summarization.

In analyzing the sounds from aircraft overflights, just over a minute's signal was digitized at a rate of 1024 samples/s. Successive power spectra were computed from blocks 1024 samples long and overlapped 50%. These were normalized relative to the strongest spectral peak within the set of spectra (121) in order to derive a waterfall spectrogram spanning the 1 min segment of overflight sounds (see Fig. 27, p. 90). Graphs of the aircraft sound levels vs. time were prepared for each overflight, based on the levels in the 1-min sequence of spectra. Two levels were graphed: the level in the 20-500 Hz band level, and the level in the strongest one-third octave band.

Measured Propagation Loss

Data used to determine propagation loss were (1) the signals from the monitor hydrophone in front of the J-11 projector, and (2) the recorded signals received at distances 0.1 to ~18.5 km.

Signals from the monitor hydrophone were used to calculate source levels of the tones and the transmitted samples of *Karluk* drilling sounds. ▸ During TL tests 1 and 2, the J-11 monitor hydrophone signals were measured with an AC voltmeter (true rms meter) to determine the signal level at the monitor hydrophone. The distance of this hydrophone from the projector varied over the range 0.75-0.85 m from day to day. The spherical spreading model was used to determine the level at a standard distance of 1 m, the reference distance for all source levels quoted in this report. (The spherical spreading model assumes that sound level varies with the square of the distance.) ▸ For TL tests 3-5, the monitor hydrophone signals were tape recorded and later analyzed by computer. This procedure provided spectrum analysis of the emitted signals, 8.5 s averaging, and accurate determination of source levels. This procedure also provided source levels for each third-octave component of the broadband drilling sounds during TL tests 3-5.

The signals recorded at the various receiving stations were analyzed using the computerized spectrum analysis procedures described above, with 8.5 s of averaging. For each TL test and range, Greeneridge determined the received level of each of the eight pure tones, the sample of *Karluk* drilling sounds, and the ambient noise immediately before and/or after these sounds were projected. For TL tests 4 and 5, Greeneridge also determined the received levels of the audible HFM sweeps at each range. BBN repeated some of these measurements and, for the more distant receiving stations where the signals were inaudible, also applied a specialized cross-correlation signal processing technique in an attempt to detect and measure the HFM signals (see below).

The difference between the source level and received level of corresponding signals was the transmission loss. This difference was determined for each tone and for each of the prominent third-octave bands in the *Karluk* drilling noise. Thus, acoustic transmission loss was measured as a function of frequency and range on five occasions.

Matched Filtering of HFM Signals

The Concept.--Where background noise is high, a signal processing technique known as matched filtering can be used to obtain an estimate of signal energy (intensity) with better noise rejection than is possible with conventional methods. A common signal used for matched filtering is an HFM (Hyperbolically Frequency Modulated) sweep. HFM sweeps centered at 100, 200, 500, 1000, 2000 and 5000 Hz were projected during all transmission loss tests. The HFM signal is unique in that it is doppler invariant. Matched filtering can be performed without having to account for any doppler shift in the received signal. Any doppler shift is observed in the matched filter results as a shift in the apparent arrival time. Thus, the waveform forgoes arrival time accuracy in order to be doppler-insensitive (Rihaczek 1986).

Matched filtering is effectively a correlation operation between the received acoustic signal and a "replica". The acoustic signal is the signal received by a hydrophone. It contains a number of components including, for example, the signal transmitted by the underwater sound source (modified by transmission loss effects), ice cracking, wave slap, and biological noise. The purpose of matched filtering is to obtain a measure of the signal energy received from the underwater source without including the acoustic energy from the other noise sources. The measurement is obtained by correlating the acoustic signal with a "replica" of the signal transmitted by the source. The key difference between an energy estimate obtained from a matched filter and an energy estimate obtained by conventional methods is that the matched filtering process uses phase information in the replica to aid in discriminating signal vs. noise.

The processing gain G, which is the increase in signal-to-noise ratio obtained by the filtering process, is

$$G = 10 \log(W \cdot T)$$

where W is the bandwidth of the signal and T is the signal duration. The noise attenuation AN is

$$AN = 10 \log (W)$$

where W is the replica bandwidth.

Signal Processing.--Processing of the received HFM signals involved two steps: digitization and matched filtering. Analog tape dubs of the signals received during transmission tests were played on a Sony Model M5D cassette tape recorder. The signal was filtered using antialiasing filters and digitized on a MASSCOMP 5500 data acquisition computer system. One HFM sweep was digitized for each range-frequency combination of interest. The specific sweep to be digitized was chosen based primarily on the amount of biological noise (mainly bearded seal calls). If the signal was not audible, digitization was begun based on the known time of the transmission. Matched filtering was performed on a general purpose VAX/VMS computer using existing software, which performed a frequency domain "fast convolution" and plotted the results (e.g. Fig. 16).

Two different signals were available for use as the replica for the matched filter: the signal monitored by the hydrophone <1 m from the projector, or an ideal replica representing the original HFM waveform. If the magnitude response of the projector is flat and its phase response is linear over the band of the signal, then the signal monitored in the water will be identical to that sent to the projector. In this case, either signal can be used as the replica with equal success. However, if these conditions are not met, or if the source distorts the signal through some non-linear process, then the filtering should be performed with a replica that represents the signal that was actually put into the water--i.e. the signal from the monitor hydrophone near the projector.

Preliminary analyses were conducted to compare the results obtained using these two types of replica signals. The original "ideal" HFM waveform proved to be a better replica than did the signal monitored by the hydrophone near the projector. The signals from the monitor hydrophone had apparently been degraded somewhat by tape speed flutter and multiple dubbing steps. Use of the ideal HFM waveform provided the greatest improvement in signal-to-noise (S:N) ratio. The following two subsections summarize our tests of the effectiveness of this procedure. Based on this analysis of effectiveness, the matched filter procedure was used to obtain measurements of received signal levels at some of the distant receiving stations during TL Tests 4 and 5.

Test Results with Strong Signals.--Figure 16 shows a matched filter analysis of a 1000 Hz HFM signal, as monitored near the projector, with itself as the replica. In this artificial case, the signal and replica are identical. The peak in the spectrum (Fig. 16A) is broad because the signal is a tone whose frequency oscillates within the 1/3-octave band centered at 1000 Hz. Because the signal and replica are identical, the matched filter produces a single "clean" cross-correlation peak (Fig. 16B). Based on the characteristics of that peak, the received level of the signal can be derived.

This is the ideal type of result that might be obtained from a matched filter analysis. However, in practical circumstances, the received acoustic signal is not identical to the replica, and the filter output is not as "clean" a peak as shown in Fig. 16B. It is common to see several peaks. This generally indicates that several components of the signal arrived along different propagation paths. If there is more attenuation along one propagation path than along another, the peak corresponding to the more attenuated component will be

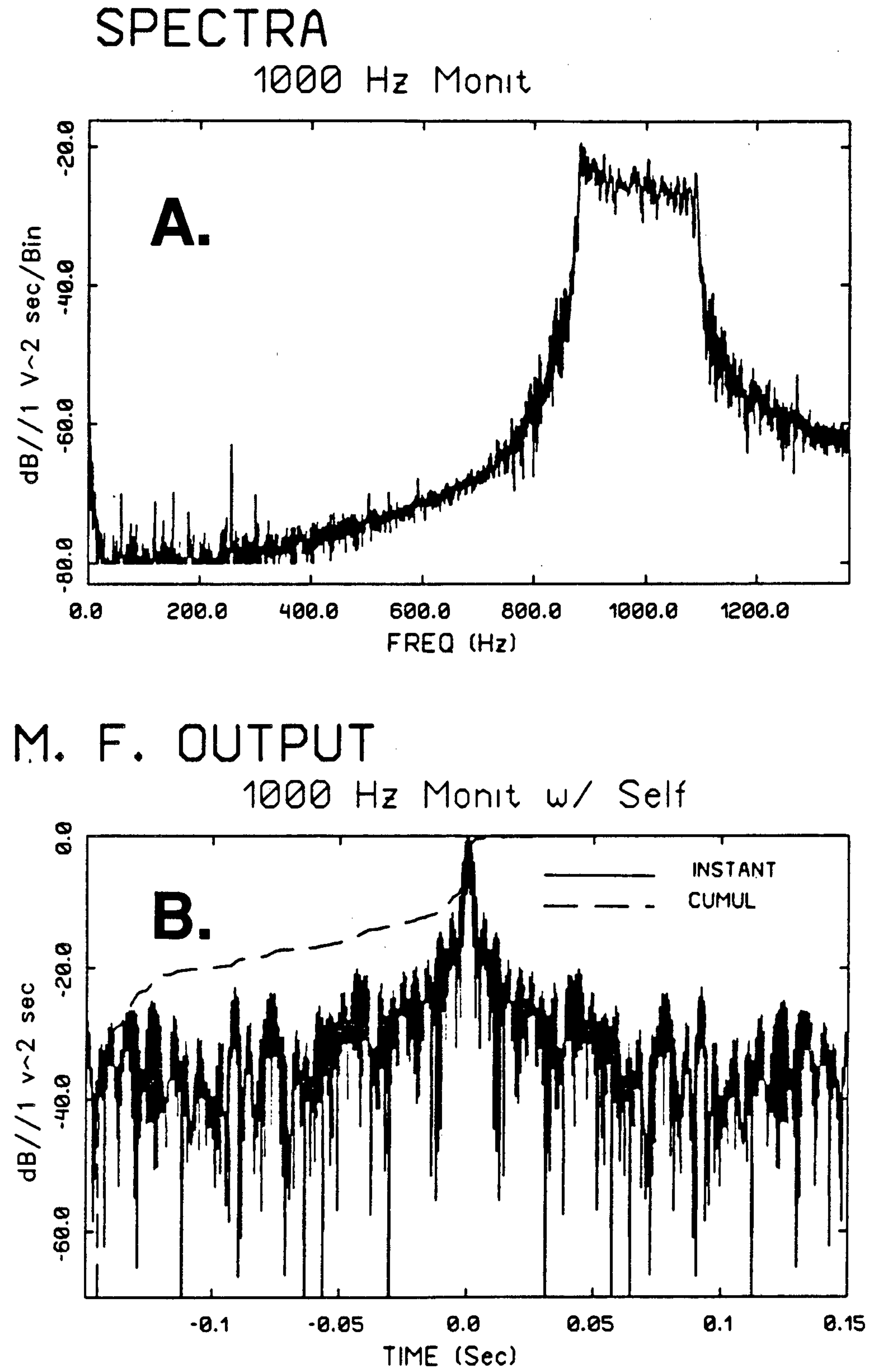

Fig. 16. Matched filter processing of projector monitor signal during transmission of 1000 Hz HFM signal, with itself as the replica. (**A**) Power spectrum. (**B**) Matched filter cross-correlation output.

lower. Sometimes the peak is smeared over a wider time interval; this is common in ducted environments where there is temporal spreading of the signal.

Figure 17 shows the results for the 1000 Hz sweep as received 100 m from the projector during TL Test #4. The ideal HFM waveform was used as the replica. Because the data were obtained only 100 m from the projector, the S:N ratio was high and the analysis produced a single sharp peak (Fig. 17B).

Representative Low S:N Data.--An example of the effectiveness of the matched filter method when the signal-to-noise ratio is low is given in Fig. 18. This analysis was based on the 2000 Hz sweep received at range 9.2 km during TL Test #5. Again, the ideal HFM waveform was used as the replica. The received level of this HFM sweep could not be measured by conventional methods at this range (see Table 11B, p. 122), although a pure tone at 2000 Hz was audible and measurable at this range (Table 12, p. 123).

The bandwidth for this 5 s sweep was 460 Hz, so the theoretical processing gain (G) was 33.6 dB and the noise attenuation (AN) was 26.6 dB. Based on conventional analysis methods, the measured RMS band-limited intensity for this waveform was -39.5 dBV. When the signal was passed through the matched filter, the noise level should have been reduced by 26.6 dB, so the average matched filter noise output intensity should have been -66.1 dBV. In fact, the matched filter output in Fig. 18B shows a peak occurring at time 0.07 s with signal energy of -48.8 dBV-s; the average noise intensity is around -65 dBV, as predicted. Thus the matched filter was able to extract a signal whose energy was about 16 dB below the noise energy in the corresponding band. The output S:N was 17 dB.

In conclusion, matched filter processing of the HFM waveforms was effective in improving the energy estimates of the signals received at distant sites where S:N ratios were low. The matched filter processing of the data worked better when the replica was the ideal waveform than it did with the monitored signal as the replica. This was attributable to tape speed flutter in one of several record and playback stages associated with the monitor hydrophone signals. The flutter problem presumably could be overcome in a future application of this method; ideally, a digital recorder should be used. However, even in the absence of a suitable monitored signal replica, the ideal waveform replica appeared to be adequate for the processing.

Received levels of pure tones generally were measurable using conventional methods at distances as great as those where HFM signals were measurable with matched filter methods (see Physical Acoustic Results, later). However, the HFM approach is expected to provide a better representation of the average transmission loss of sounds within a 1/3-octave band. The HFM signal oscillates across a 1/3-octave band, whereas a pure tone involves only a single frequency. Different frequencies within a single 1/3-octave can be attenuated differentially, so pure tone TL data do not necessarily apply to all frequencies within the associated 1/3-octave band.

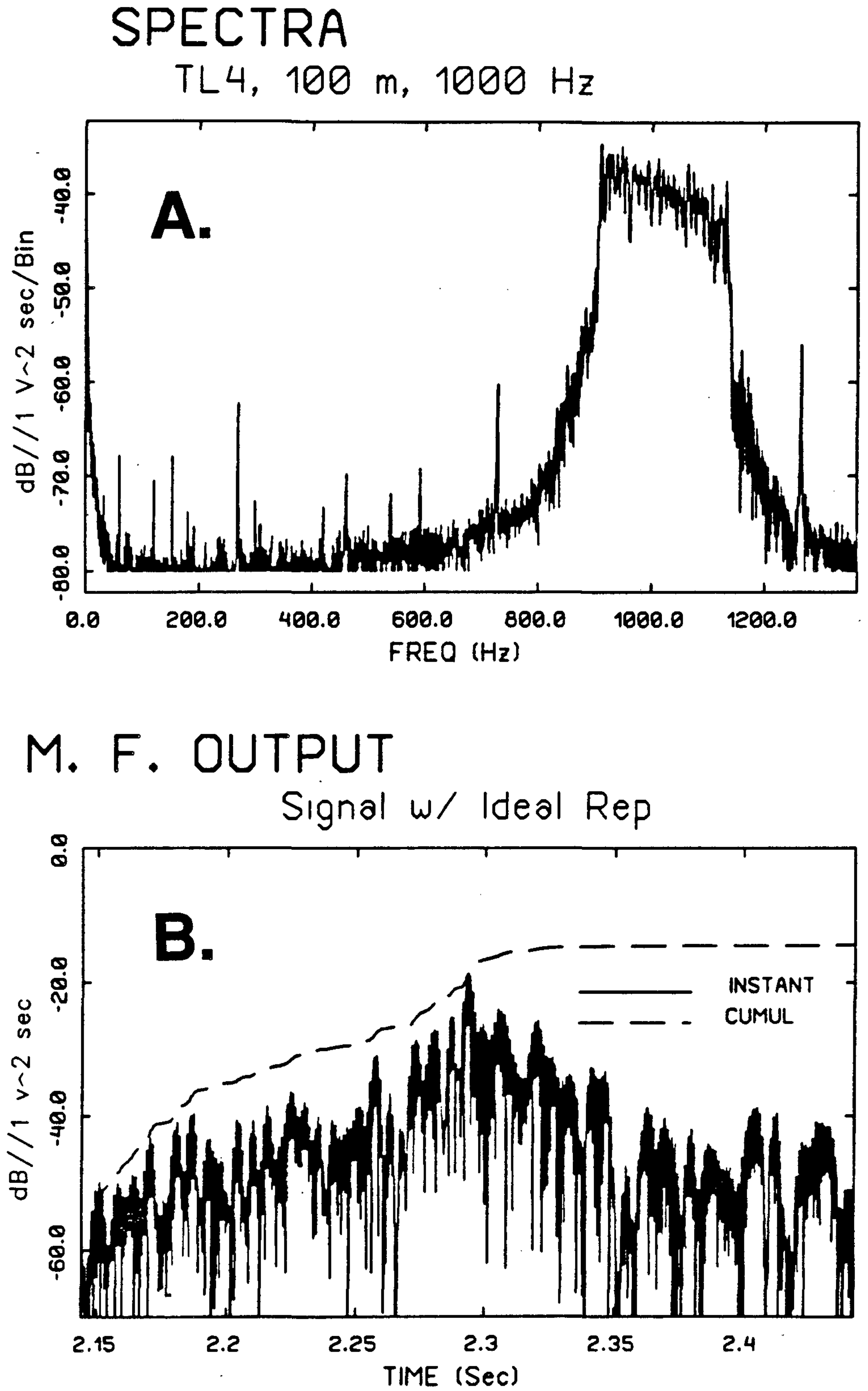

Fig. 17. Matched filter processing of signal received at 100 m range during transmission of 1000 Hz HFM signal with the ideal source waveform as the replica (high S/N ratio). (A) Power spectrum. (B) Matched filter cross-correlation output.

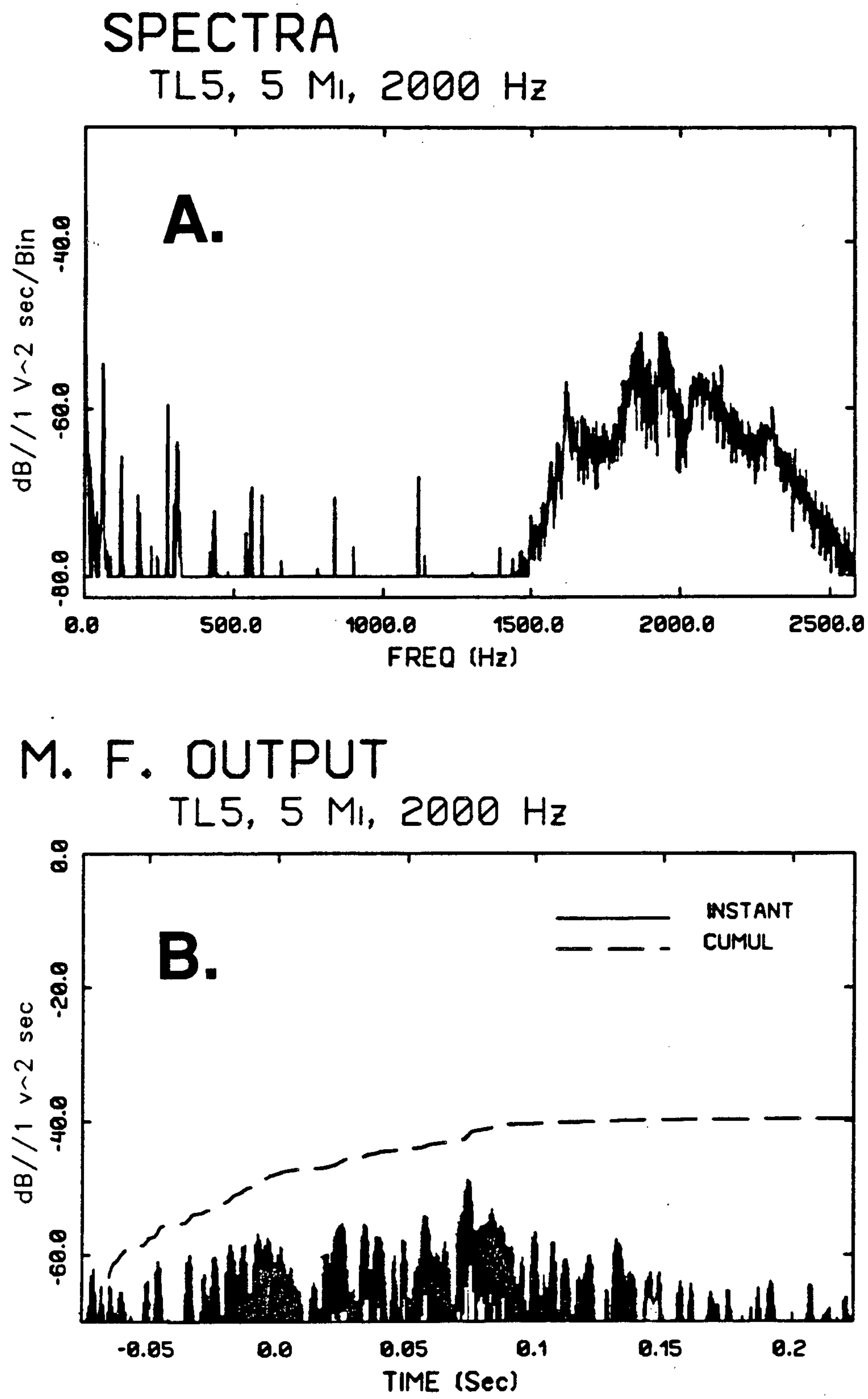

Fig. 18. Matched filter processing of signal received at 9.2 km range during transmission of 2000 Hz HFM signal, with the ideal source waveform as the replica (low S/N ratio). (**A**) Power spectrum. (**B**) Matched filter cross-correlation output.

Propagation Modeling

A version of the Weston/Smith sound propagation model was used to derive "best-fit" transmission loss curves, based on the TL data obtained by Greeneridge during TL Tests 4 and 5. When the TL data are obtained with a projector whose source level is known, as was the case in this study, it is possible to obtain the "true" transmission loss by subtracting the known projector source level from the measured received level. When a Weston/Smith model is fitted to such data, it is a semi-empirical model. Its predictions are partly controlled by theoretical considerations, but are strongly affected by coefficients derived from the empirical data.

The Weston/Smith model, as originally formulated by Weston (1976), Smith (1986) and Malme et al. (1986), was modified by incorporating a term that provides for the additional scattering loss incurred during sound transmission under ice (Milne 1967). Scattering loss is a function of the roughness of the underice surface. Scattering loss is also proportional to the average number of reflections along the transmission path, which is inversely related to the water depth. To minimize the influence of depth variations along different propagation paths on scattering parameters, a normalization factor was obtained by assuming that the average number of reflections (bounces) in the transmission path is proportional to R/H_{av}; H_{av} is the average water depth along the transmission path and R is the range.

A computer program was used to fit the Weston/Smith model to the empirical data by regression methods. The following coefficients were estimated:

b,	a parameter related to the bottom reflection coefficient
Sin ϕ_c,	the sine of the critical angle
L_s(eff),	the effective source level (includes site effects)
A_b,	the scattering term due to ice roughness (dB/bounce)

The difference (if any) between the known source level at 1 m, L_s, and the effective level estimated by the regression model, L_s(eff), represents the local transmission anomaly, in dB:

$$A_n = L_s(\text{eff}) - L_s$$

The local transmission anomaly results from the effect of the local bottom and surface conditions in producing a reverberant sound field near the source. This field may either be stronger or weaker than predicted by the transmission model, producing a positive or negative value for A_n.

The TL data obtained by Greeneridge included the results of conventional analyses of received HFM sweep tones, pure tones, and samples of the *Karluk* drilling noise analyzed by 1/3-octaves. The rms pressure average of these three test signals was determined at 50, 100, 200, 500, 1000, 2000 and 5000 Hz for each transmission range during TL Test 4, and separately for TL Test 5. These average TL values were then used in the regression analyses that determined the coefficients of the Weston/ Smith models. Above 200 Hz, only the pure tone and sweep tone data were used because the *Karluk* signals data did not contain significant energy above 315 Hz. BBN's matched-filter estimates of the received levels of HFM sweeps at certain long-range stations were considered when interpreting the Weston/Smith results, but were not included in the datasets used to develop those models.

The Weston/Smith models for different frequencies and for TL Tests 4 and 5 were compared to help evaluate the factors affecting transmission loss in the study area. In addition, the semi-empirical Weston/Smith results were compared with preliminary theoretical models of transmission loss that had been derived for the study area (see Appendix A) before any site-specific empirical data on TL were available.

Aerial Reconnaissance and Surveys

General Approach

Aerial reconnaissance and surveys were a necessary component of the work required to meet specific objective 4, "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 determine 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 of the difficult ice conditions (see "Study Area--Ice Conditions"), it was not prudent to leave the ice-based crew on the ice overnight. There was no open lead along the landfast ice edge until late in the study period, and even then the whales were not moving along the nearshore side of the lead (see p. 149). Locations of open water amidst the pack ice varied from day to day. Consequently, the first priority each day was to determine 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 might bring whales to the projector site. On the few occasions when a more extensive area of open water was present, the survey consisted of a series of closely spaced parallel transects west of the projector site.

The need to avoid disturbing whales near Barrow necessitated setting up the projector ≥60 km east of Pt. Barrow (see specific objective 7 and "Study Area--Selection Criteria"). On several days during early and mid May 1989, there were no locations with suitable ice conditions or whales ≥60 km to the east. On these dates, aerial surveys were extended west, closer to Pt. Barrow, in order to find whales. When this was successful, behavior of undisturbed whales was documented and vertical photographs of bowheads were sometimes taken. We avoided flying over or west of the location where the North Slope Borough's whale census was to be based even though ice conditions prevented a census during May 1989.

Survey Methods and Data Recording

Aerial surveys were conducted from 1 to 30 May 1989 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 an internal auxiliary fuel tank for extended endurance, 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), a ventral camera port, and an intercom system for communication among the three observers and two pilots. The aircraft was flown at ~200 km/h airspeed and, when possible, at 305 m (1000 ft) or 457 m (1500 ft) above sea level (ASL). When ceilings were lower than 305-457 m, the maximum possible altitude below the cloud layer was maintained. During the midday 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 457 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).

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

When a whale was sighted, the observer notified other members of the crew over the intercom. In most cases 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 of bowheads seen from the helicopter during ferry flights were noted.

Behavioral Observations

Aerial Observations

On 17 occasions in May 1989, the aerial observation procedures of Richardson et al. (1985a,b) were used to observe the behavior of bowhead or white whales, as required to meet specific objectives 4 and 6. Three observers in the Twin Otter aircraft circled high above the whales. If possible, the aircraft circled at 457 m ASL, which has been found to be high enough to avoid significant aircraft disturbance to bowheads, at least during summer and autumn. (As noted on p. 210, sensitivity to the observation aircraft appeared to be no greater during this spring study than during previous summer and autumn work.) Airspeed during circling was 165 km/h. The 17 behavioral observation sessions ranged from 0.1 to 3.3 h in duration and totalled 25.6 h. During five of these sessions on four different days, 9.2 h of aerial observations were conducted near the ice camp in co-ordination with broadcasts of drilling platform sounds (see Fig. 19 on p. 72).

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, 1985a; Richardson et al. 1985b, 1987b; Koski and Johnson 1987). For white whales, we recorded as many as possible of the same variables. However, blows by white whales often could not be seen while circling at 457 m altitude. For white whales, more emphasis was placed on recording direction and speed of movement relative to the ice edge and sound projector, and less emphasis was placed on recording respiration, surfacing and dive variables.

The third observer, also on the right side during behavioral observations, operated sonobuoy receiving equipment and, whenever whales were at the surface, an 8-mm video camera. The video camera was a Sony CCD-V11 with 12-72 mm lens and 2x teleconverter. 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. On most occasions the behavioral dictation on the intercom was recorded onto the audio channel of the video tape recorder.

Behavioral data were transcribed from audiotape between flights, and the videotape was examined 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 for details). These records were hand checked, and then entered into an IBM-compatible microcomputer for computerized validation and analysis.

For bowheads, 380 surfacing and 242 dive records were obtained by aerial observers during 1989. Of these, 218 and 124 were obtained under "presumably undisturbed" conditions. Of the data obtained under "potentially disturbed" conditions, 90 surfacing and 69 dive records were obtained during playback of the drilling platform sounds. In addition, 44 surfacing and 23 dive records were obtained during periods when the observation aircraft was at an altitude <457 m and may have disturbed the whales.

For white whales, the aerial observers recorded 458 surfacing and no dive records. Of these surfacing records, 400 were obtained during playbacks of drilling sounds, and 23 during presumably undisturbed conditions. We recorded 451 orientations and 284 estimates of the relative speed of movement of individual whales.

Ice-based Observations

Observations of bowheads or white whales were conducted by ice-based observers on nine occasions from 30 April to 30 May 1989 to help meet specific objectives 4, 5 and 6. Two observers used binoculars and a land surveyor's theodolite to search for whales. The observation site was usually on an ice ridge 2-5 m ASL, and was ≤300 m from the sound projector. When whales were spotted, one observer watched the whales and dictated observations to the second observer, who recorded all relevant observations onto data sheets or into field notebooks.

The digital theodolite (Lietz/Sokisha Model DT20E, 20 second precision) was used to determine successive positions of whales and seals in relation to the sound projector. Upon arrival at the daily site, the theodolite was set up on the highest ice perch within ~300 m of the projector and ~20 m of open water. The height of the theodolite was determined each day by taking a horizontal reading from a vertical stadia rod at the projector location. Theodolite bearings were measured in degrees, minutes and seconds from the horizontal zero (referenced to magnetic north) and a vertical zero (referenced to the leveling device on the theodolite). 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 by simple trigonometry (Felleman and Chumbley 1983). This calculation did not correct for the curvature of the earth, but this error is small for the combinations of perch heights and the short (<2 km) distances involved in the 1989 observations of whales (Table 2). A whale 500 m from the observers at an observation height of 2 m ASL would be 5 m farther than the distance calculated by the simple formula. 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. However, the lack of reliable data on vertical temperature gradients in the air over a lead prevents an evaluation of refraction error.

Table 2. Underestimation of distances calculated from theodolite data (in m) when curvature of the earth corrections are not used*.

Perch Height	Distance from Perch (m) 100 m	500 m	1000 m	1500 m	2000 m
1 m	0.09	10.0	94.6	448	N/A
2 m	0.04	5.1	42.9	163	485
3 m	0.04	3.3	27.8	101	270
4 m	0.03	2.5	20.5	72.9	188
5 m	0.02	2.0	16.3	57.1	145
6 m	0.01	1.6	13.5	47.0	118

* Formula for curvature of the earth from Kewalo Basin Marine Mammal Lab., HI.

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. Depending upon the width of the lead and the height of the perch, the waters within ~2-3 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 for as long as they remained 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.

Bowhead Photogrammetry and Photo-identification

We photographed bowhead whales using the calibrated vertical photography technique developed by LGL (Davis et al. 1983). Two types of information were obtained from the photographic images:

1. The sizes of individual whales were determined. This was important because whale behavior is expected to vary with the age and size of whales and because the timing of bowhead migration past Barrow is partially segregated according to size (Nerini et al. 1987).

2. Information on local movements and residence times of whales was obtained by photographing individual whales on more than one occasion. This information is important when interpreting potential effects of simulated industrial disturbance.

This work provided some of the information needed to meet specific objectives 4 and 6.

The acquisition of information on local movements and residence times of bowheads was enhanced by close cooperation between this study and the NMFS/NMML aerial photography project (specific objective 7). Before and after each flight, representatives of the two project teams met in Barrow and discussed their plans or findings. When both teams were flying, they maintained VHF radio contact. In this way it was possible to avoid having both groups photograph at the same location on the same day. In addition, we were able to direct the NMML crew to certain whales that were too far from the sound projector to be a priority for us, and the NMML crew occasionally pointed out situations that might afford us a useful research opportunity. Each crew benefited from weather reports provided by the other crew, given that there are no weather stations NE of Barrow.

Field Procedures

In 1989, we obtained vertical photographs at the conclusions of 5 of the 17 behavioral observation sessions and on 5 other occasions when behavioral observations were not conducted. During photography sessions, the aircraft descended to 145 m (475 ft) ASL. Because of the potential to disturb whales during photography from this low altitude, whales were not photographed if they could potentially be observed by the ice-based observers after the aircraft left, or if the aircraft might return to the same area to conduct further behavioral observations later the same day.

During photo sessions, the aircraft circled the location of the whales and flew directly over them at ~165 km/h when they surfaced. Photographs were taken with a hand-held Pentax 6x7 cm camera with a 105 mm *f*2.4 lens pointed directly downward through a ventral camera port. Ektachrome 200 color positive film was used for all photography. The firing of the camera was audible to all observers through the intercom system. As each photograph was taken, the pilot read the altitude from the analog display of the radar altimeter and the left observer recorded the time and radar altitude from a digital display in the rear of the aircraft. The altitude as read by the pilot was recorded by the right front observer. The two altitude records were later compared to ensure that no recording error had occurred. In addition, as the camera was fired the front observer recorded the time and position from the VLF navigation system. Two identical calibrated camera/lens systems were used; the system that was used was recorded for each roll of film.

Calibration photographs of a target of known dimensions were obtained to permit calculation of actual whale sizes from the photographs. The target was spread out on land in a "+" configuration, with a length and width of 20.0 m. Five photographs of the target were taken with each camera/lens system.

Size Measurements

Images of bowhead whales and calibration targets were measured directly from the processed film to the nearest 0.01 mm using a Zeiss binocular dissecting microscope and a stage micrometer. The average of three blind replicate measurements was used to calculate the dimensions of the target or whale using the following equation from Jacobson (1978):

$$\text{Calculated length} = \frac{\text{Altitude x Image size}}{\text{Focal length of lens}}$$

The dimensions calculated from the above formula were then corrected for distortion caused by the focal plane shutter in the camera (see Davis et al. 1986b).

Calculated target sizes (corrected as above) were regressed against the known target measurements to give the following regression equation:

$$\text{Actual length} = (\text{Calculated length} - 0.034)/0.99533$$

This equation corrects for systematic biases, e.g. in the altitude values derived from the aircraft's radar altimeter, and was used to convert calculated whale lengths to actual lengths. Recent studies (Koski and Johnson 1987; Nerini et al. 1987; Dave Withrow, NMFS, pers. comm.) have indicated that radar altimeters may give slightly different altitude readings over land and water. The observed differences appear to be consistent for a given individual radar altimeter. Altitude readings were ~1.3% lower over water than land, resulting in a slight underestimation of whale length (Nerini et al. 1987). However, it is not known whether the difference is the same for all altimeters made by the same manufacturer, or for altimeters made by different manufacturers. The lengths presented in this report are based on calibration data from targets photographed over land, with no correction for any land/water effect.

The quality of the measurements varied from one photograph to another because of the varying postures of the whales and changing sea state and lighting conditions. The repeatability of each measurement was assigned a grade from 1 to 6, following Davis et al. (1986b). A grade 1 measurement was the highest quality measurement.

Individual Identification

Koski and Johnson (1987), Richardson et al. (1987b) and Koski et al. (1988) have shown that vertical photographs can be used to document short-term (within day), medium-term (day-to-day), and long-term (year-to-year) movement patterns of bowhead whales. Photographs obtained by us and NMML, when combined, might provide information on rates of movement of bowheads subjected to playback experiments in comparison to those not subjected to playback experiments.

Individual whale images from this study were enlarged as 5x7 inch custom prints and labelled. Each whale image was assigned a re-identification grade, as in previous studies (Davis et al. 1983, 1986a,b). Photographs of whales that would be recognizable in another photo of similar or better quality taken in another year were grade A. Photos of whales that would be recognizable in a photo of similar or better quality taken the same day or within a few days were grade B. Photos of whales that probably would be unrecognizable in another photo of similar or better quality were grade C.

The grading of prints involved a subjective assessment of focus, resolution, lighting, glare, reflection, sea state and posture of the whale, as well as distinctiveness of the whale's markings. A poor quality photo of a very distinctively marked whale might be graded A while an excellent photo of a whale with no distinctive markings might be graded C. We have not considered grade C photographs in this analysis. Each grade A and B print was then assigned to one of 20 files depending upon the amount of white on the lower jaw and in the tail region (Davis et al. 1983; Braham and Rugh 1983).

Each whale image was compared to all others acquired in this study, and to all images that NMML obtained after 7 May 1989. Each grade A whale image was also compared to our collection of summer and autumn photos acquired since 1981 in the Canadian and Alaskan Beaufort Seas. In these inter-year comparisons, whale images were compared to all other images in the same file and in "adjacent" files containing images with similar characteristics.

Playback Experiments

Playbacks were conducted to meet specific objective 4, "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. Playbacks were conducted on 12 occasions. During seven of these sessions, no white whales or bowheads were seen while the projector was operating, although during two of these seven sessions (16 and 21 May) whales were observed before the projector was on. During one session (19 May) observations of whales were obtained only from the ice camp because low cloud cover prevented aerial observations from altitude ≥457 m. During the remaining four sessions (14, 23, 27 and 29 May) observations of whales were obtained by both the ice-based and aircraft-based crews.

Playback Equipment and Procedures

A single broadband J-11 projector was used for all playback experiments. The J-11 can produce a source level up to about 164-166 dB re 1 μPa-m without distortion. Its effective bandwidth is 20-12,000 Hz. It 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.

In order to operate the amplifier and other electronic equipment for a significant length of time, it was necessary to use a generator rather than batteries to provide power. The generator produced significant airborne noise, but little of this noise was transmitted into the water because of attenuation by the snow-covered ice. Noise levels produced by the 2.2 kW Honda gasoline-powered generator were low in comparison to those from the projector (see "Physical Acoustics Results", p. 97).

Each day when weather and ice conditions permitted, the ice camp was established on the pack ice along a lead near the east end of an open water area. When possible, the camp was placed to the east or northeast of whales located by aerial reconnaissance. The J-11 projector and ancillary equipment, the sound recording and monitoring equipment, and the theodolite were set up. This process normally required at least 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. (We did not plan to start the projector when whales were within a few hundred meters, since the sudden onset of industrial sound would not be typical of an actual oil-industry site, and might cause startle reactions that could confound interpretation of later behavioral observations.)

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 view of ice-based observers, 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 1-2 km) 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. It was usually about 1 km.

Acoustical Monitoring

Sound levels reaching whales during playback experiments were measured and/or estimated using several techniques, as described in preceding subsections on "Acoustical Field Methods" and "Acoustical Analysis Procedures". 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 described earlier, along with mathematical models of transmission loss, provided estimates of received level as a function of range under varying ice conditions. When direct measurements of sounds reaching the whales were impractical, the TL data and models were used to estimate the received levels.

The observation aircraft was equipped to drop sonobuoys near whales that were under observation from the aircraft, and to record the telemetered data on sounds being received by the whales. This permitted accurate measurement of sound levels received by some of the whales observed from the aircraft.

We also maintained a monitor sonobuoy about 1 km from the projector site during most periods when the ice camp was operating. (However, on 29 May an ice pan crushed the monitor sonobuoy, so these data were not available for much of that day.) The telemetered signals were monitored periodically at the projector site and also aboard the observation aircraft when it was in the area. These data provided a direct measurement of received industrial noise level at one distance from the projector. On 14, 19, 23 and 27 May, the monitor sonobuoy was positioned close to the point of closest approach of some of the whales that were observed, thus providing direct information about sound levels received by the whales. Even when the whales did not approach close to the monitor sonobuoy, the received sound levels there provided a calibration point for estimates made using propagation models.

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. We then intended to observe their movements and behavior as they approached and passed the projector.

Because the projector had to be re-established 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 attempted to prevent the two primary behavioral observers in the aircraft from knowing whether or not the sound projector was operating. This "blind" observation protocol was only imperfectly achieved because of difficulties in isolating the aerial observers from some radio communications. The behavioral observers usually did not know exactly when the projector was turned on or off. However, during the major part of each observation session near the projector site, they were aware that the projector was operating. This knowledge would affect few (if any) of the data collected. Estimated swimming speed was one variable that required a partly subjective judgement, and thus there is the possibility of observer expectancy bias in this case.

In addition to the aerial observations, 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. The most valuable data obtained from the ice-based observations were data on the closest point of approach to the projector and on the precise 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 or limited aircraft endurance.

Because of their proximity to the projector site, the ice-based observers 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.

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. Because there were few opportunities for playbacks in 1989, 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. However, we recognize that this type of control information is needed to confirm that any observed changes in behavior are attributable to the noise rather than to the physical presence of the ice-based crew. The 1990 field program will include a number of control observation periods.

GENERAL CHRONOLOGY OF 1989 FIELD ACTIVITIES

Preliminary Sound Propagation Tests, 25-30 April

Plans called for preliminary sound propagation tests to be conducted from 25 to 30 April 1989. The main field program, including noise playback experiments, was to extend from 1 to 28 May. The purpose of the late April work was to determine whether the actual radius of detectability of the projected sounds was any greater than that predicted before the field season (*cf.* Appendix A). If not, the main field program could go ahead during May as planned.

The necessary research permit was issued by the National Marine Fisheries Service on 24 April, and fieldwork started on 25 April, as scheduled. The ice-based crew used the helicopter to conduct an initial ice reconnaissance ENE of Barrow. The purpose was to select prospective sites for the preliminary sound propagation tests (otherwise known as Transmission Loss or TL tests). Logistical constraints and poor weather prevented conduct of the first TL test until 29 April (Table 3).

TL tests were conducted on 29 and 30 April. There was no open water along the edge of the landfast ice, so the sound projector was set up on an ice pan alongside a small open-water area amidst the pack ice. The projector sites on the two days were 79 and 86 km, respectively, ENE of Barrow (Fig. 19). The projector was set up on the same ice pan on the two successive days, but the ice had drifted eastward several kilometers in the interim. Recording sites were to the west and northwest of the projector. Almost all of the region around the projector (>99%) was covered by pack ice. The ice was especially heavily ridged a few kilometers west of the projector site. Two bowheads were heard (but not seen) during the TL test on 29 April. Three bowheads were seen near the projector during the TL test on 30 April. One of these was observed just before and during broadcast of some of the test sounds.

The acoustic data from these two preliminary TL tests were analyzed in Barrow on 1 May to determine how far the drilling sounds were audible under the ice. Because the sounds attenuated rapidly with increasing distance and were inaudible within 5-10 km, it was concluded that the main field program could go ahead as planned.

Main Field Program, 1-30 May 1989

The Twin Otter and its crew were at Barrow by the evening of 30 April. On 1 May an aerial survey was conducted to determine the general ice conditions in the study area and to test the equipment aboard the Twin Otter. On 2 May the aerial crew conducted a survey ENE and NE of Barrow and found little open water and no bowheads. Because no bowheads were found, playback experiments were not practical. Hence, the ice-based crew conducted a third TL test amidst smoother ice slightly north of the first two TL test sites (Fig. 19).

Table 3. Summary of daily activities and weather and ice conditions, 25 April-30 May 1989.

	Ice-based Crew									Aircraft-based Crew						
				Number of										Number of		
Date	Ferry Flights	Transm. Loss Test	Karluk Projections	Bowheads	White Whales	Location	Other	Ice Conditi.	Overall Ceiling/ Visibility	Cloud Survey (h)	Obser. Sess.	Behavior Photogr. (h)	Location	Bowheads	White Whales	Other
25 Apr	1			0	0	ENE	Ice reconnaissance									
26 Apr	0								Poor visibility							
27 Apr	0						-35° with wind chill factor									
28 Apr	0								Poor visibility							
29 Apr	6	#1		2 heard	0	71°38' 154°34'	In hole among pack ice. Whales before transmission	>99%								
30 Apr	8	#2		3 (1)*	0(30)*	71°36' 154°25'	In hole among pack ice	>99%								Aircraft crew arrives at Barrow
1 May	0						Analyze TL data	>99%		1.7			Survey ENE of Barrow	0	0	
2 May	6	#3		0	0	71°39' 154°31'		>99% Narrow cracks	Fog until noon; clear, excellent visibility PM	1.9			Survey ENE of Barrow	0	22	Few open water areas
3 May	6		P1	0(1)	0(7)	71°44; 153°54'	Broadcast into area of thin ice	>99%	Fog until 12:00; clear, excellent visibility PM	2.5	2.5	0.3	71°33'-71°39' 155°28'-155°30'	25	53	Whales within restricted area (i.e. within 60 km of Barrow)
4 May	0								Low ceiling. Poor visibility							
5 May	0								Low ceiling. Poor visibility	2.4			Survey ENE of Barrow	0	36	
6 May	4		P2	0	0	71°37' 154°46'	Broadcast into open lead among pack ice	99% Small leads	Low ceiling E of 155° (~180 m). Clear at Barrow.	2.3	1.8		71°40' 155°57'	10	71	Bowheads within restricted area. Low ceilings E of 155°.
7 May	6		P3	0	0	71°37' 154°58;	Broadcast into refrozen lead among pack ice	>99%	Clear or high cloud	2.7	1.5		Survey ENE of Barrow 71°47' 155°29'	3	69	
8 May	0						No flight due to lack of open water	100%	Clear or high cloud	2.1			Survey ENE of Barrow	0	12	Virtually no open water, froze overnight

Continued....

Table 3. Continued.

	Ice-based Crew									Aircraft-based Crew						
				Number of										Number of		
Date	Ferry Flights	Transm. Loss Test	Karluk Projec-tions	Bowheads	White Whales	Location	Other	Overall Ice Conditi.	Cloud Ceiling/ Visibility	Survey (h)	Behavior Obser. Sess.	Photogr. (h)	Location	Bowheads	White Whales	Other
9 May	2	#4		0	0	71°50' 155°30'	TL conducted at thinly refrozen lead. Bowheads and white whales heard but not seen.	100%	Fog AM; clear PM	3.1			Survey ENE of Barrow	0	55	
10 May	0							100%	Low ceiling all day. Poor visibility in AM.							
11 May	0							>99% Narrow lead developing	Low ceiling. Poor visibility in snow, fog.							
12 May	0							95% Offshore leads developing	Low ceiling. Poor visibility in snow, fog.	1.9	0.1		Survey ENE of Barrow 17°55' 155°04'	4	68	
13 May	0							85% Large lead along ice edge E of Barrow	Low ceiling. Poor visibility in snow, fog.	1.5			Survey ENE of Barrow	1	31	
14 May	4		P4	5(3)	15(2)	71°46' 155°03'	Broadcast into open lead among pack ice	85% Offshore lead in pack ice	Good visibility. Ceiling >460 m until 15:00; 245-305 m after 16:00	2.3	5.5	0.4	Survey ENE of Barrow 71°38'-71°50' 154°45'-155°50'	26(1)**	160(8)	Projection experiment
15 May	0							85-90% Some new ice over night	Low ceiling. Poor visibility in snow	2.0		0.2	Survey ENE of Barrow 71°48' 155°08'; 71°54' 154°28'	5	133	
16 May	4		P5	2	13(6)	71°44' 155°08'	Broadcast into open lead among pack ice	90% Some new ice over night	Ceiling 180-305 m. Visibility good with occasional snow	2.2			Survey ENE of Barrow	0	22	

Continued....

Table 3. Continued.

	Ice-based Crew									Aircraft-based Crew						
				Number of										Number of		
Date	Ferry Flights	Transm. Loss Test	Karluk Projec- tions	Bowheads	White Whales	Location	Other	Overall Ice Conditi.	Cloud Ceiling/ Visibility	Survey (h)	Behavior Obser. Sess.	Photogr. (h)	Location	Bowheads	White Whales	Other
17 May	2			0(3)	24	71°35' 155°44'	Poor weather to east; helicopter overflight sound measurement	95% New ice formed over night	Ceiling 120-180 m to east. Visibility good to poor in snow	2.2			Survey ENE of Barrow	1	96	
18 May	1			0(1)	0		Flight aborted due to poor visibility	>90%	White-out conditions in some areas. Ceiling variable 150-460 m.	2.1		1.0	Survey ENE of Barrow 71°34'-71°36' 156°00'-156°15'	15	22	
19 May	4		P6	4	2	71°40' 155°23'	Broadcast into large open lead in pack ice	>90%	Ceiling 150 m. Visibility good (~18 km) except for occasional snow squalls.							
20 May	0							90% Lead formed along landfast ice edge	Variable, low ceilings and poor visibility	1.3			Survey ENE of Barrow	0	0	
21 May	8		P7	0	7	71°35.8' 155°16'	Broadcast along N side of main lead	85% Strong winds move ice	Very low ceiling (100 m) in blowing snow	1.5			Survey ENE of Barrow	0	22	
22 May	0							80%	Low ceiling. Poor visibility in snow and fog							
23 May	4		P8	3(3)	7(5)	71°37' 155°02'	Broadcast into large open lead among pack ice	80% Lead 8 km wide NE of Barrow	Variable ceiling 130-450 m. Good visibility	3.8	4.5		Survey ENE of Barrow 71°38' 155°07'; 71°42' 154°41'	5(2)	76(3)	Projection experiment
24 May	0							80% N of lead 90% pack ice	Low ceiling with icing in AM. Good visibility below 140-275 m later	1.4	1.1		Survey ENE of Barrow 71°36' 155°56'	6	59	Test difar sonobuoy. Major lead along fast ice edge NE of Barrow for rest of study.
25 May	4	#5		0	0(1)	71°37' 154°39'	Broadcast into small lead among pack ice N of main lead	80%	Low ceiling and poor visibility until late in day when ceiling lifts to 200-280 m	1.8		1.3	Survey ENE of Barrow 71°36' 155°38'; 71°33' 154°54'; 71°33' 155°12'	10	51	Aerial photogrammetry calibration

Continued....

Table 3. Concluded.

	Ice-based Crew									Aircraft-based Crew						
				Number of										Number of		
Date	Ferry Flights	Transm. Loss Test	Karluk Projections	Bowheads	White Whales	Location	Other	Overall Ice Conditi.	Cloud Ceiling/ Visibility	Survey (h)	Behavior Obser. Sess.	Photogr. (h)	Location	Bowheads	White Whales	Other
26 May	1			0	0		Flight aborted due to fog	80%	Ceiling and visibility variable in fog							
27 May	4		P9	0(1)	14	71°35' 154°34'	Broadcast among pack ice N of main open lead.	80%	Clear	3.8	5.5	0.9	Survey ENE of Barrow 71°33' 154°33'; 71°33' 154°42'	17	52(8)	Normal Behavior Projection experiment
	4		P10	0	0	71°35' 154°45'	Broadcast along N side of main lead.						71°38' 155°18'			Projection experiment
28 May	4		P11	0	0	71°35' 154°54'	Broadcast along N side of open lead. Helicopter and Twin Otter overflight sound measurements.	80%	Clear AM. High cloud PM.	5.3	0.7	0.6	Survey ENE of Barrow 71°39' 155°00'	3	5	
29 May	4		P12	0(2)	2	71°41' 154°49'	Broadcast into small lead among pack ice on N side of main open lead	80%	Some high cloud. Good visibility.	3.9	2.5	0.3	Survey ENE of Barrow 71°42' 155°08'	4	77	Projection experiment
30 May	2			0	0		No projections due to unstable ice conditions	80% Lead partially blocked by pans	Clear	2.1			Survey ENE of Barrow	0	0	

* Numbers in parentheses indicate whales observed during ferry flights.

** Numbers in parentheses indicate additional whales seen from the aircraft that were also seen from the ice-based camp.

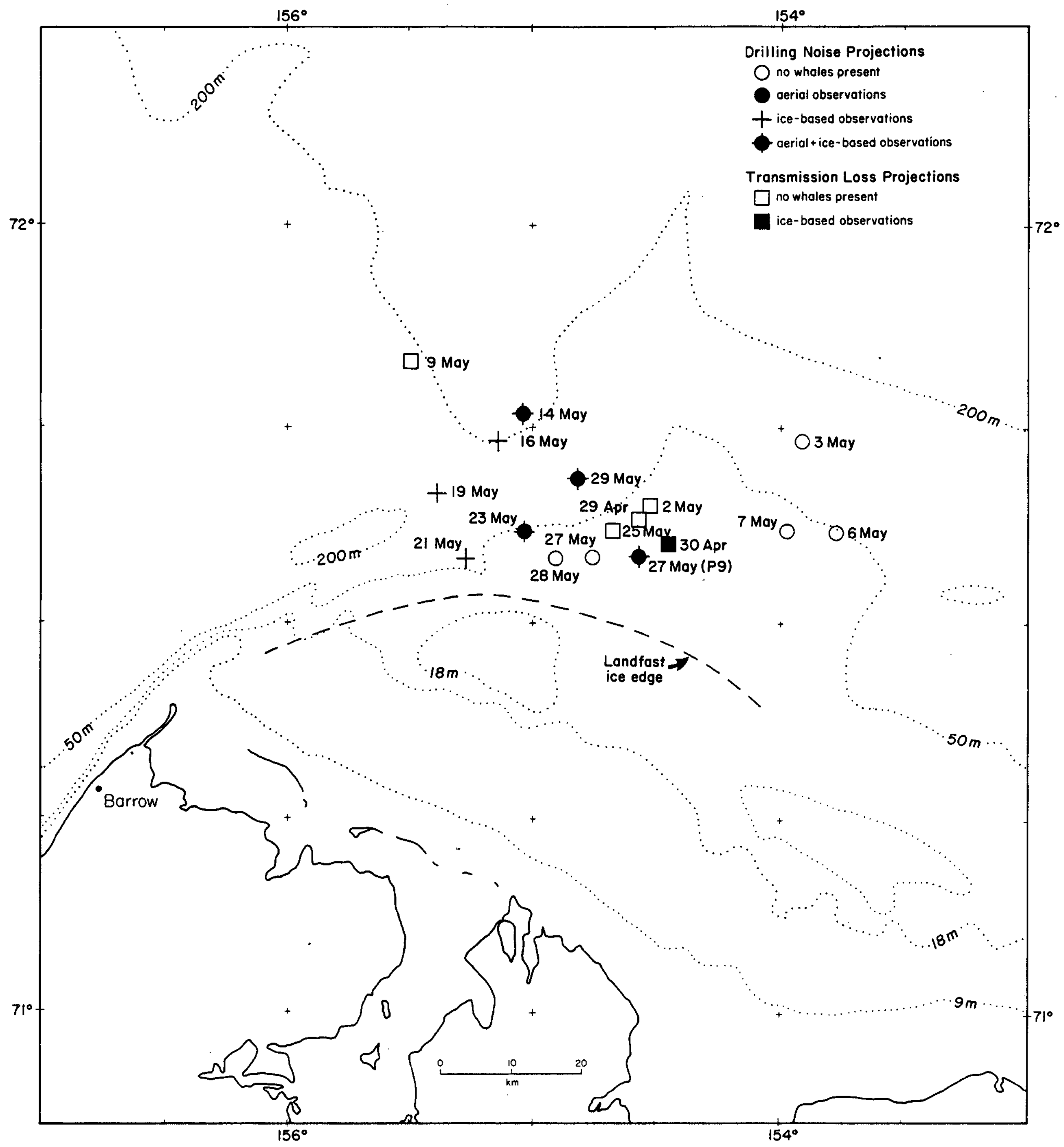

Fig. 19. Locations where ice-based crews conducted transmission loss tests or broadcast drilling sounds, 29 April-29 May 1989. Locations are approximate because of ice drift during the course of each day's work.

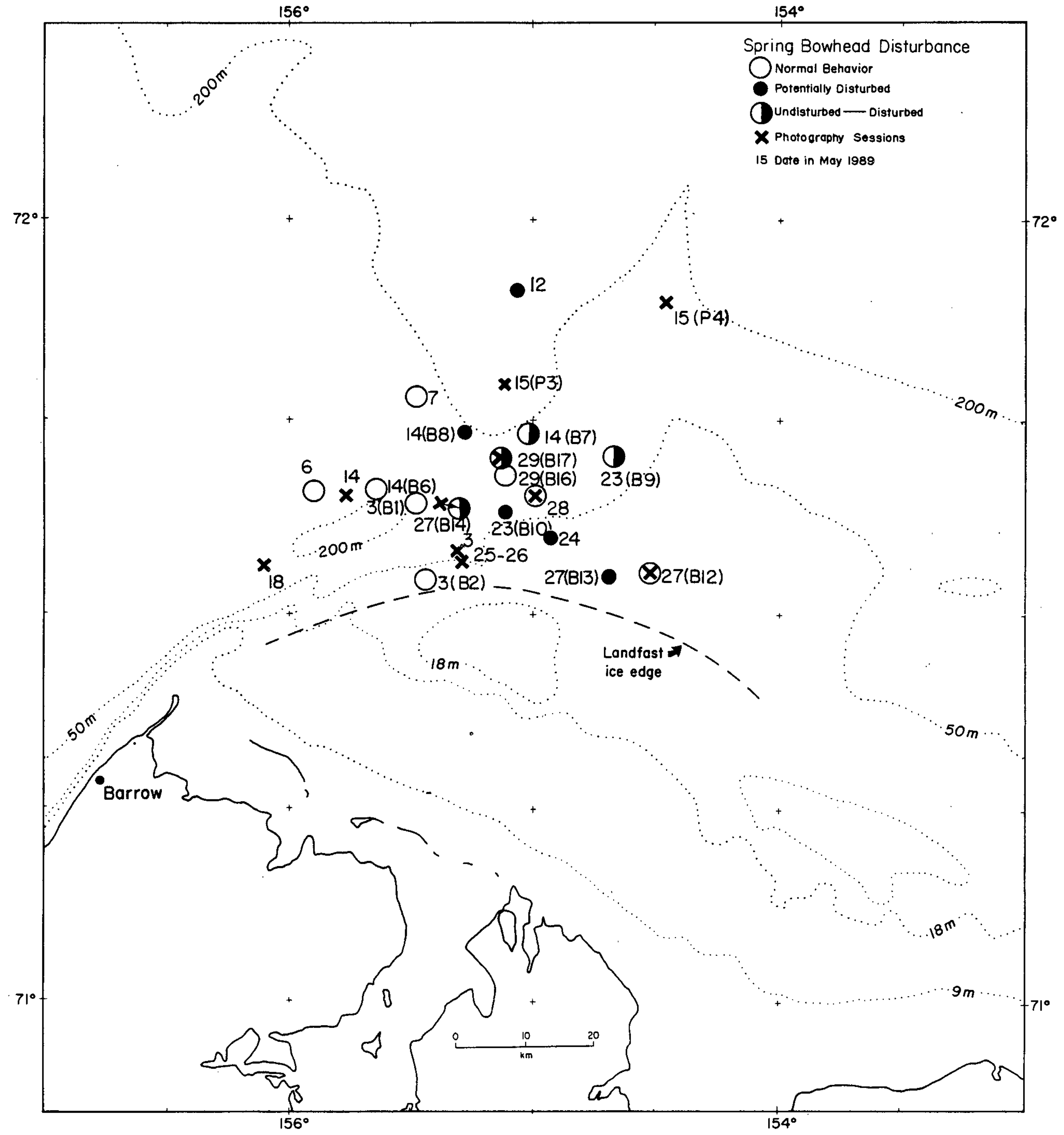

Fig. 20. Locations where behavior of bowhead whales was observed and vertical photographs were obtained by the aerial crew, 3-29 May 1989. Numbers outside parentheses indicate the date (in May 1989). Numbers in parentheses refer to behavior observation session numbers in Table 4 (prefixed by a B) or photo session numbers (P) where more than one occur on the same day.

On 3 May the ice-based crew projected drilling sounds into a recently refrozen lead found amidst the pack ice the previous day (Fig. 19). However, no whales were seen near the projector. After conducting extensive surveys near the projector site and not finding any bowheads, the aerial crew observed bowheads engaged in various activities closer to Barrow (Table 4, Fig. 20). About 25 bowheads were seen; this was the second-highest daily total for the entire field season. Most of the whales were migrating through narrow intermittent leads, which made it impossible for us to observe specific whales for prolonged periods. Playback experiments were not possible in this area because it was less than 60 km from Pt. Barrow.

Low ceilings and poor visibility prevented useful work on 4 and 5 May. However, on 5 May the aircraft crew conducted a low-level survey to monitor ice conditions and to select a potential site for an experiment the next day.

The weather cleared at Barrow on 6 May, but low cloud persisted east of longitude 155°W. The ice-based crew projected drilling sounds into an open lead amidst the pack ice and saw no whales. Because of the low ceilings at the projector site, the aerial crew conducted behavioral observations of bowheads closer to Barrow where the ceiling was higher but where drilling sounds could not be projected into the water.

The weather was clear and cold on 7 May and again little open water and few whales were found. The ice-based crew set up the sound projector along a refrozen lead in the pack ice, but saw no whales. After finding no whales near the projector, the aerial crew observed the behavior of three migrating and resting bowheads elsewhere.

Cold temperatures and light winds persisted on 8-10 May, and the few small open water areas that had been present froze. No bowheads were seen by the aerial crew on 8 or 9 May. The ice-based crew conducted a fourth TL test far offshore along a thinly refrozen lead. The ice was much smoother at this TL site than at previous sites.

From 11 to 13 May the weather was poor with low ceilings, fog and light snow. Leads were starting to develop in the offshore pack ice. Another lead started to develop near the edge of the landfast ice off Barrow, but did not extend east of Pt. Barrow. Few bowheads but numerous white whales were seen during surveys conducted by the aerial crew.

The weather cleared on 14 May, and the projector was set up along a long lead oriented NNE-SSW through the pack ice (Fig. 19). Large numbers of both bowheads and white whales were found in the vicinity. This was the first occasion when all of the factors necessary for a playback experiment were present at the same place and time, *viz* an area of open water 60+ km beyond Pt. Barrow, whales in that area, and cloud ceiling high enough (≥460 m) to allow behavioral observations from the air. The aerial crew observed two bowheads as they migrated from 4.7 to 0.5 and 0.9 km from the operating projector. Numerous white whales were also observed as they approached and passed the operating projector.

Table 4. Summary of aerial behavioral observation sessions, 1989.

Date 1989	Behavior Obs. Sess.	Location	Obs. Period	No. of Bowheads		General Activity	Predominant Orientation	Predominant Speed of Travel	Size Classes	Disturbance	Water Depth (m)	Sea State	% Ice	
				Circle	Area								in circle	overall
3 May	1	71°33'-155°28'	16:13-17:36	3-5	15	some migrating slowly, some sexual activity	mostly E	slow	unknown	none	40	0	85	98
3 May	2	71°39'-155°30'	18:11-19:15	3	3	1 water-column feeding, 2 resting	variable	zero-resting	2 adults 1 small sub-adult	none	190	0	95	98
6 May	3a	71°40'-155°57'	15:53-16:34	4	9	probably migrating	NE	medium	unknown	none	120	0	95	99
	3b	71°40'-155°55'	16:55-17:05	2	9	probably migrating	NE and S	medium	unknown	none	130	0	95	99
	3c	71°39'-155°59'	17:12-18:10	3	9	sexual activity	variable	slow-medium	adults	none	150	0	95	99
7 May	4	71°47'-155°29'	15:58-17:25	3	3	migrating and resting	NNW	zero-medium	unknown	none	260	0	99	>99
12 May	5	71°55'-155°04'	12:55-13:01	1	1	migrating	NE	medium	unknown	potential aircraft	280	1	85	95
14 May	6	71°40'-155°40'	10:34-11:08	3	8	no forward motion-slow	NE to SW	zero-slow	unknown	none	205	1	80	85
14 May	7	71°44'-155°01'	11:29-14:47	3	6	migrating - one whale breaching	NE	medium	adults plus subadults	none to 11:58 *Karluk* play-back after 11:58	170	2	35	85
14 May	8	71°38'-71°50' 154°45'-155°50'	16:37-18:12	var.	var.	probably migrating	ENE	slow-medium	unknown	potential aircraft	160-233	1	90-95	85

Continued...

Table 4. Concluded.

Date 1989	Behavior Obs. Sess.	Location	Obs. Period	No. of Bowheads		General Activity	Predominant Orientation	Predominant Speed of Travel	Size Classes	Disturbance	Water Depth (m)	Sea State	% Ice	
				Circle	Area								in circle	overall
23 May	9	71°42′- 154°41′	12:22- 14:32	1	1	migrating	E	medium	unknown	aircraft to 12:40; post-aircraft to 13:10; then none; TL 13:59-14:09; then distant *Karluk* playback	72	1	90	80
23 May	10	71°38′- 155°07′	15:40- 18:02	1-3	4	2 migrating 2 local movement	W and SE	slow	3 adults 1 calf	*Karluk* playback	90-115	1	80	80
24 May	11	71°36′- 154°56′	19:12- 20:17	2	4	migrating	NE	slow-medium	1 adult, 1 calf 2 unknown	potential aircraft disturbance	42	0	85	80
27 May	12	71°33′- 154°33′	9:22- 11:47	4	6	migrating	variable NE to SE	slow-medium	2 adult-calf pairs	none	42	1	50	80
27 May	13	71°33′- 154°42′	12:47- 14:58	2	2	migrating	variable NE to S	slow-medium	adult/calf	*Karluk* playback Sonobuoy drop at 13:30	42	1	65	80
27 May	14	71°38′- 155°18′	19:29- 20:23	2	4	local movement	variable	slow	adult/calf	none to 20:11 Sonobuoy drop after 20:11	140	0	0	80
28 May	15	71°39′- 155°00′	11:46- 12:30	2	3	local movement	SW to NW	slow	adult/calf	none	95	1	80	80
29 May	16	71°42′- 155°08′	10:28- 10:46	2	2	local movement	SE to S and W	slow	adult/calf	none	160	1	85	80
29 May	17a	71°42′- 155°08′	12:20 13:58	2	2	local movement	SE to SW	slow	adult/calf	none to 12:53; TL 12:53-13:02; then distant *Karluk* playback. Sonobuoy drop at 13:21	170	0	85	80
	17b	71°42′- 155°08′	14:50- 15:23	2	2	local movement	S to SW	slow	adult/calf	distant *Karluk* playback	160	1	85	80

The ice-based crew observed a single white whale by theodolite for 25 min as it approached and retreated from the projector. Several additional bowheads and white whales were observed for briefer periods by the aerial and ice-based crews. Aerial observations of whales passing the projector were curtailed when the cloud ceiling descended below 460 m during the afternoon. Even so, more bowheads and white whales were seen on this date than on any other (Table 3).

The ceilings were low and the visibility was poor for most of 15 May. In the evening, the visibility improved and the aerial crew conducted a reconnaissance ENE of Barrow. Five bowheads and 133 white whales were seen.

On 16 May, the visibility was generally good, but ceilings were too low for aerial observations. The ice-based crew observed a mother/calf bowhead and three white whales, which were potentially disturbed by the Bell 212 helicopter during deployment of equipment. White whales (n=16) were observed before the projector was started, but no whales were sighted while the projector was operating.

On 17 May, the ceiling was low 60+ km east of Pt. Barrow where we could conduct playback experiments. Therefore, the ice-based crew deployed hydrophones from an ice pan 55 km NE of Barrow to measure the levels and characteristics of underwater sounds from Bell 212 helicopter overflights at different altitudes.

On 18 May, the ceiling was again too low to conduct aerial observations of whale behavior. Leads through the offshore pack ice were starting to open again, but the only bowheads found during an aerial reconnaissance (n=15) were in the lead near the fast ice edge 30 km NE of Barrow. We took 13 vertical photographs of these whales.

The ceilings remained low on 19 May, again preventing aerial observations of behavior. However, the ice-based crew set up the sound projector on the pack ice and projected drilling sounds into an L-shaped lead. Four bowheads and two white whales were observed approaching the operating projector. A theodolite was used to track these whales. One bowhead approached to within 100-120 m of the operating projector.

From 20 to 22 May, the ceilings remained low and visibility was poor in snow and fog. Strong winds moved the offshore pack ice, resulting in more open water amidst the pack ice. The lead along the fast ice edge finally extended eastward into our study area. Aerial surveys on 20 and 21 May detected no bowheads and few (22) white whales. On 21 May, the ice-based crew set up the projector on the pack ice edge along the north side of the main nearshore lead between the pack and landfast ice. However, no bowhead or white whales were seen while the projector was operating.

On 23 May, the ice-based crew set up near the east end of an area of open water area amidst the pack ice a few kilometers north of the nearshore lead. Whales exposed to noise from the projector were observed from both the ice and the observation aircraft. A mother and calf bowhead heading north and west away from the projector were observed when the projector was broadcasting drilling sounds. Two additional bowheads were observed as close as 2.3 and 2.4 km from the operating projector, migrating eastward past it. About 50 white whales were watched as they migrated from 5 km WNW to 0.5 km NNE of the operating projector. They then hesitated for 12-20 min, dove under the pan supporting the projector, surfaced 300-600 m SSE to SE of the projector, and continued migrating E.

Low ceilings persisted throughout 24 May. The aerial crew conducted a low level survey ENE of Barrow and sighted numerous white whales and several bowheads. We tested the operation of a DIFAR (directional) sonobuoy from the Twin Otter near 4 bowheads and 11 white whales.

On 25 May, the ice-based crew set up the projector on the pack ice just north of the nearshore lead, but no whales were sighted nearby. Hence, a fifth sound transmission loss test was conducted along the north edge of the nearshore lead. The aerial crew sighted 11 bowheads (including 5 cow/calf pairs) and 51 white whales in or near the nearshore lead closer to Barrow. The cow/calf bowheads were all photographed. Low ceilings and fog prevented work on 26 May.

On 27 May, the projector was initially set up along a secondary lead ~4 km north of the main nearshore lead. The projector was again set up on the pack ice because the bowheads seen ~60 km beyond Pt. Barrow in mid-late May had all been either in the pack ice or along the north edge of the nearshore lead--none were on the south side of the nearshore lead. On 27 May, the ice-based crew saw 14 white whales but no bowheads pass the projector. All bowheads sighted by the aerial crew were moving along the north edge of the main nearshore lead, about 4 km south of the projector. Hence, during late afternoon the projector was moved to a large pan along the north side of the lead. In the evening, no whales were found near the projector operating at its new location, so the aerial crew observed a mother/calf pair ~20 km WNW of the projector. This same cow/calf pair was observed on 28 and 29 May (identity photographically confirmed).

Weather conditions were ideal on 28 May. The projector was set up on the pack ice near the north side of the main E-W nearshore lead. However, no whales approached the projector. The aerial crew observed the behavior of a mother/calf pair 13 km NW of the projector. Late in the day, the underwater sounds from both the Bell 212 helicopter and the Twin Otter were measured by flying at several altitudes over hydrophones deployed from the ice camp.

Fieldwork had been scheduled to end on 28 May. However, at that time the ice and weather conditions were improved from those in early and mid-May, and at least a few bowheads and white whales were still migrating through the study area. Hence, after consultation with MMS, we decided to continue fieldwork for two or three more days.

On 29 May, the weather was again good. The projector was set up on the largest available lead amidst the pack ice a few km north of the main nearshore lead. Two white whales passed the projector before it was operating, but no whales were seen near the projector afterwards. A mother/calf bowhead and 50 migrating white whales were observed about 10 km west of the projector, where drilling sounds were not detectable. The bowheads remained in that area through the day.

The weather was clear on 30 May, but it was windy and the ice conditions had changed dramatically. The main nearshore lead was partially blocked by large pans and the pack ice was shifting rapidly. The ice-based crew set up the projector on a large pan along the north side of the flaw lead. However, no whales were seen in the area by either crew. Because of the unstable and dangerous ice conditions, the ice-based crew returned to Barrow without projecting drilling sounds.

Summary of Field Activities

The helicopter-supported crew worked from the ice on 18 days between 29 April and 30 May. They conducted sound transmission loss experiments on five days, aircraft noise measurements on two days, and projected drilling noise into the water for several hours on each of 11 days (Table 3). On five of these days, we observed bowhead whales that were within the area ensonified by the projector: during the TL test on 30 April and the periods with drilling noise on 14, 19, 23, 27 May. On four days, white whales were also observed near the operating projector (14, 19, 23 and 27 May). Whales near the projector were observed from the ice on 30 April and 19 May, and from both the ice and the air on 14, 23 and 27 May. Overall, the aircraft crew conducted reconnaissance surveys on 24 days from 1 to 30 May, behavioral observations on 10 days, and photogrammetry on 8 days (Table 3).

The absence of a nearshore lead until 20 May in 1989, and the absence of a consistent whale migration corridor even after that date, reduced the number of opportunities for observations of whales passing the sound projector. By the last week of May, when weather and ice conditions were greatly improved, few whales were passing. All ice-based work had to be done from the pack ice rather than from the edge of the landfast ice. This was necessary because there was no lead along the edge of the landfast ice until 20 May, and even then the whales continued to migrate farther offshore. Nonetheless, useful data were obtained on the reactions of bowhead and white whales to drilling noise, and most of the desired physical acoustic data were collected. The availability of full-time helicopter support allowed us to work from different locations on the moving pack ice each day.