Ecological Research Associates

BEHAVIOR, DISTURBANCE RESPONSES AND FEEDING OF BOWHEAD WHALES *Balaena mysticetus* IN THE BEAUFORT SEA, 1980-81

by

LGL Ecological Research Associates, Inc.
1410 Cavitt Street
Bryan, Texas 77801

for

Bureau of Land Management
U.S. Dept. of the Interior
18th and C Streets, N.W.
Washington, D.C. 20240

Contract No. AA-851-CT0-44

August 1982

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PROJECT RATIONALE, DESIGN AND SUMMARY*

By

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INTRODUCTION

The imminence of offshore exploration for oil and gas in the Alaskan part of the Beaufort Sea has raised concerns about the potential for disturbance of bowhead whales. The bowhead, Balaena mysticetus, is a baleen whale inhabiting cold northern waters. Historically, five substantial populations existed: Western Arctic, Davis Strait, Hudson Bay, Okhotsk Sea, and Spitsbergen. The western arctic stock inhabits the Bering, Chukchi and Beaufort Seas off the shores of Alaska, the U.S.S.R., and Canada. All five populations were heavily exploited by commercial whalers, and all are now seriously reduced. Only the western arctic population continues to be of substantial size, yet even it is considered to be rare and endangered under U.S. legislation, in Canada, and by the International Whaling Commission. Until very recently, the size of the western arctic stock was believed to be in the range 2264-2865 individuals (Braham et al. 1979, 1980b; Krogman et al. 1981), but the latest estimates are somewhat higher (Davis et al. 1982; Intern. Whal. Comm. in press).

SEASONAL MOVEMENTS OF WESTERN ARCTIC BOWHEADS

The western arctic bowheads winter in the Bering Sea and migrate north and east to the eastern Beaufort Sea in spring. Off the northwest coast of Alaska, the spring migration occurs in a narrow corridor along the annually recurring nearshore lead (Fig. 1). Once past Point Barrow, the bowheads move east far offshore--well to the north of the icebound nearshore area where exploration for oil and gas is imminent (Braham et al. 1980a; Ljungblad et al. 1980). It is not known whether these whales are too far offshore to hear or to be disturbed by waterborne noise produced by industrial activities in the nearshore zone. (The nearshore waters are shallow and propagated sound is, therefore, subject to greater losses than in deep ocean water.)

During summer (late June to early September) most bowheads of the western arctic population are in the eastern part of the Beaufort Sea off Canada. In the commercial whaling era in the 19th century, many bowheads apparently summered in the Chukchi and western Beaufort Seas off Alaska (Townsend 1935), but nowadays bowheads are not present in significant numbers off Alaska in summer (Braham et al. 1980c; Dahlheim et al. 1980).

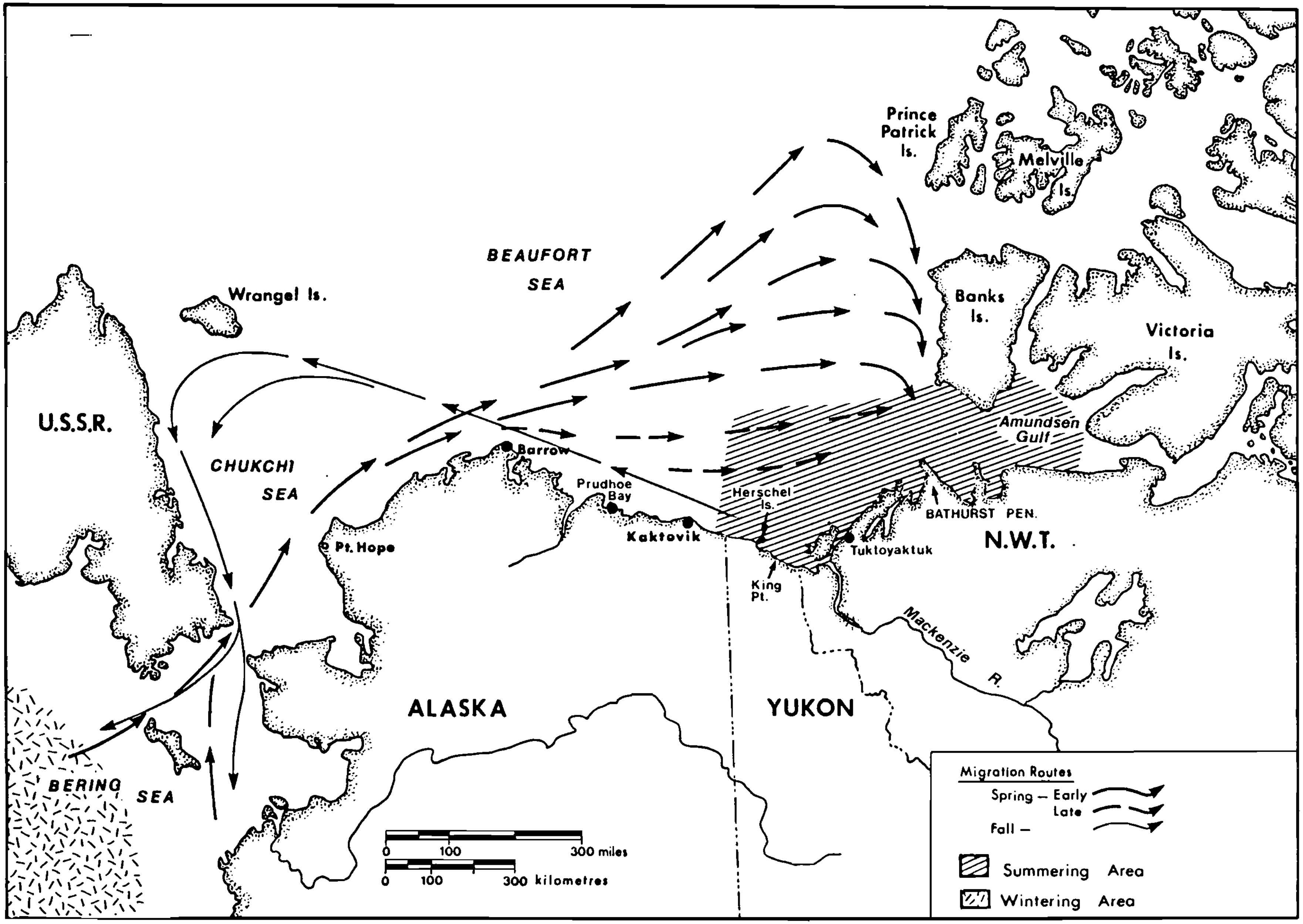

Figure 1. Generalized pattern of seasonal movement of the western Arctic population of bowhead whales.

The eastern Beaufort Sea is believed to be a major feeding area for bowheads (for review, see Fraker and Bockstoce 1980), but previous to 1980 there had been no comprehensive studies of bowheads in that area. Offshore drilling for oil and gas has been going on in the eastern Beaufort for nearly a decade, initially from artificial islands in shallow water but since 1976 also from drillships operating farther offshore during the open water season.

In September and October, bowheads migrate west from the Canadian Beaufort Sea into the Alaskan Beaufort, and then into the Chukchi Sea. Feeding apparently continues off northern Alaska (Lowry et al. 1978; Lowry and Burns 1980). During fall, unlike spring, there is open water along the north coast of Alaska. Many bowheads move west and/or feed within 25 km of the shore (Braham et al. 1977; Ljungblad et al. 1980). Thus, bowheads are more likely to come close to offshore industrial activities in the Alaskan Beaufort in fall than in spring.

Some bowheads apparently continue west from Point Barrow to the Soviet side of the Chukchi Sea in fall (Braham et al. 1977; Johnson et al. 1981). Bowheads may continue to feed there before moving south to wintering grounds in the Bering Sea.

POTENTIAL FOR DISTURBANCE

Little is known about responses of whales to boats, aircraft or offshore industrial activities. The scientific and popular literature contains anecdotal reports about whale behavior near some of the potential sources of disturbance, but there have been almost no systematic studies of behavioral reactions to disturbance--even for the common and more accessible species of whales. Furthermore, the longer term effects of disturbance on population distribution, productivity and survival are virtually unstudied for any whale species, and are difficult to assess in any direct way.

Except for oil spills, direct collisions or harassment, it is generally agreed that underwater sound is the by-product of marine petroleum operations that holds the greatest potential for affecting whales. Whales and other marine mammals live in an environment where light conditions and visibility are variable. Where the water is highly turbid because of fine particles from river discharges or from an abundance of plankton, or when little light is present (i.e. night or arctic winter), vision is of little value. Some dolphins, such as the Ganges River dolphin (Platanista gangetica), which lives in the highly turbid Ganges River system, are apparently completely blind.

Marine mammals seem to use sound as a primary means by which they communicate and receive information about their environment. Unlike light, sound travels very efficiently in water day or night, winter or summer, and is virtually independent of the water's clarity. In deep water, intense low frequency sounds such as those from some mysticete whales are transmitted especially well and with little attenuation. Mysticete sounds have been detected at distances of about 160 km (Cummings and Thompson 1971) and may travel even farther in deep water (Payne and Webb 1971). Toothed whales have a highly developed echolocation capability based on high frequency pulsed sounds (e.g., Busnel and Fish 1980), but there is little evidence that baleen whales have this capability (Thompson et al. 1979).

The very advantages of underwater sound that have been so useful to marine mammals give rise to the potential for problems related to underwater industrial sounds, since such sounds are also transmitted efficiently over relatively long distances. Virtually every activity involving the operation of machinery or use of explosives or other high-energy charges in and near the ocean has the potential for generating underwater sound. Some industrial sounds are quite intense, and many have high energy at the low frequencies used by baleen whales. Distant shipping is the dominant source of ambient noise in the 20-200 Hz band in most of the world's oceans, and onshore industrial activities can be a significant additional source in nearshore waters (Wenz 1962; Ross 1976). The 'Industrial Noise' section of this report includes a review (and new information) about noises propagating into the water from sources associated with offshore oil and gas exploration and production. These sources include boats and ships (including icebreakers in the arctic), aircraft, seismic exploration, offshore drilling, dredging, etc. Some of these types of noise are intense enough to be detectable at distances of tens of kilometres, and a few (e.g. large ships, seismic exploration) are potentially detectable for 100 or more kilometres when propagation conditions are good.

There have been no studies of the auditory sensitivity of baleen whales, but it is generally believed that their ability to detect sounds from distant conspecifics is determined by ambient noise, not by auditory sensitivity (Payne and Webb 1971; Myrberg 1978). Since industrial sounds can be the dominant source of noise at low frequencies, it follows that industrial sounds probably can limit the range at which baleen whales can hear one another (Møhl 1981; Terhune 1981).

In addition to any interference with communication, there has been speculation that noise from industrial sources might affect whales by disrupting their feeding or reproductive behavior, by excluding them from important areas, or by causing stress. The physical presence of a vessel or structure at sea might also be disturbing, although probably only at close range. The limited available evidence regarding these potential effects is summarized in the 'Disturbance' section of this report (Fraker et al. 1982), and in reviews by Myrberg (1978), Fraker and Richardson (1980), Geraci and St. Aubin (1980), Turl (1980) and Acoustical Society of America (1981). For all these reasons, the effects of offshore industrial operations may extend far beyond the sites of the industrial activities.

The largest remaining population of the endangered bowhead whale--the western arctic population--moves near or through the area of the Alaskan Beaufort Sea where offshore oil and gas exploration is beginning. This population also summers in the eastern Beaufort Sea where offshore drilling has been underway for some years. Furthermore, the migration route of these whales around northwestern Alaska in spring is through lead systems that are potential routes for future ship or tanker traffic associated with oil and gas activities in the Alaskan or western Canadian arctic. Previous to 1980, virtually nothing was known about the potential short or long term effects of industrial disturbance on bowheads.

The U.S. Government has recognized that certain species of cetaceans have been severely depleted by commercial whaling operations, and it has afforded them protection under the Marine Mammal Protection Act of 1972 and the Endangered Species Act of 1973 (ESA). Section 7 of the ESA requires that actions taken by any U.S. Government department "...do not jeopardize the continued existence of such endangered species...". Inter-agency consultations about the bowhead under Section 7 have resulted in the opinion that information is insufficient to determine jeopardy (letter from Mr. T.L. Leitzell, Assistant Administrator for Fisheries, National Marine Fisheries Service, to Mr. F. Gregg, Director, Bureau of Land Management; 24 June 1980).

APPROACH IN THIS STUDY

Tasks to be Addressed

As part of its response to the above concerns, the U.S. Bureau of Land Management awarded LGL Ecological Research Associates, Inc., a contract to investigate various aspects of the potential industrial disturbance. The date of contract award was 30 June 1980. Five tasks were given high priority:

1. Prepare a report documenting (a) present knowledge of bowhead activities, (b) potential sources of industrial disturbance during offshore oil and gas exploration and development, (c) responses of whales to such potential disturbances, and (d) related data gaps.
2. Conduct field studies to document the normal behavior of the bowhead in the Beaufort Sea.
3. Determine the responses of bowheads to close approach of boats and aircraft.
4. Determine the responses of bowheads to relevant waterborne industrial sounds by playback experiments and other means.
5. Document the physical and biological characteristics of bowhead feeding areas.

A report designed to fulfill the requirements of task 1 was submitted to BLM on 31 October 1980 (Fraker and Richardson 1980).

Tasks 3 and 4, which involve studies of the responses of bowheads to boat traffic, aircraft, and waterborne noise, form the central focus of this project. Task 2, concerning the normal ('undisturbed') behavior of the bowheads, was undertaken because behavioral reactions to disturbance can only be recognized and understood if the normal behavioral repertoire is understood. There have been no previous comprehensive studies of bowhead behavior.

Task 5, concerning the characteristics of bowhead feeding areas, was undertaken because of the assumption that feeding is a (or the) predominant activity of bowheads in the eastern Beaufort Sea. If bowheads migrate from the Bering Sea to the Beaufort primarily to feed, then it is possible that disruption of feeding behavior by disturbance, or exclusion of bowheads from certain parts of the feeding range, might have significant effects on the productivity and survival of the population. A major purpose of task 5 was to determine whether bowheads concentrate in specific areas of the Beaufort Sea that have certain physical or biological attributes (e.g. high zooplankton concentration). If so, disturbance in these areas might have especially severe effects.

Choice of Study Area

BLM selected the eastern (Canadian) part of the Beaufort Sea as the study area. Relative to Alaskan waters, this area had several advantages for the study. Bowheads are present for a comparatively long period in certain parts of the eastern Beaufort, and sometimes move close to shore (Fraker and Bockstoce 1980). Because bowheads are not hunted in the eastern Beaufort, potential conflicts between project activities (e.g. experimental disturbance trials) and local hunters are not a factor. Light and weather conditions are better for observations in the eastern Beaufort Sea in summer than in Alaskan waters in autumn.

A further major advantage of the eastern Beaufort is the fact that there is ongoing offshore drilling from artificial islands and drillships, along with support activities including shipping, dredging and seismic exploration. These activities provide opportunities for measuring the characteristics of water-borne industrial sounds and for observations of bowhead behavior near full-scale exploratory operations. For these reasons, the study was conducted in the eastern Beaufort, with the primary base at Tuktoyaktuk, N.W.T. (Fig. 1).

Project Organization

The field work necessary to address tasks 2-5 was planned as a 2-year study. Field studies were begun in August and September 1980, and continued on a somewhat larger scale from late July to early September 1981. A preliminary report on the 1980 investigations was submitted in early 1981 (Richardson [ed.] 1981). The present report contains an integrated account of the 1980-81 results and supersedes the preliminary report.

LGL Ecological Research Associates, Inc., with its Canadian affiliate, LGL Limited, was the prime contractor. LGL was assisted by two subcontractors: The New York Zoological Society assumed responsibility for task 2 (Normal Behavior Study) under the supervision of Drs. Roger Payne and Bernd Würsig. Polar Research Laboratory, Inc., principally Dr. Charles Greene, was awarded a subcontract to provide sound recording and playback equipment and technical expertise relating to underwater acoustics. LGL retained responsibility for the two 'disturbance responses' tasks, the 'feeding areas' task, and all logistical support, as well as overall responsibility. In practice, the various tasks were addressed in a closely integrated way, and most personnel--regardless of institutional affiliation--were involved in most or all aspects of the work.

Study Design

Factors Affecting Design

The design of this study was strongly influenced by several factors:

1. Before 1980, there had been no comprehensive and systematic study of the seasonal distribution of bowheads in the eastern Beaufort Sea. Previous to the present study, only the most general predictions could be made about the likely locations and dates of bowhead concentrations. Thus the logistical arrangements for the project had to be sufficiently flexible to allow us to move to areas where bowheads were concentrated.

2. The Bureau of Land Management required that the study be completed in two years (1980-81), and that substantial results be obtained the first year. Thus it was necessary to begin full-scale studies in 1980, even though greater efficiency might have been possible by conducting pilot studies in 1980 and full-scale studies in 1981-82.

3. Because of the lack of previous detailed studies of bowhead distribution and behavior in the study area, there was a danger that various proposed study approaches would be unsuccessful. Given the need to obtain substantial results for all tasks during the first year (1980), it was necessary to design considerable redundancy of approach into the study. In this way, it was hoped that if one approach to a task failed, another might provide at least some of the necessary results.

4. In the absence of much information about the behavior and disturbance responses of bowheads, it seemed appropriate to hypothesize that behavior of bowheads would be similar to that of their close relatives, the northern and southern right whales, *Eubalaena glacialis* and *E. australis*. This hypothesis provided a conceptual framework for the studies.

5. The eastern Beaufort Sea was assumed to be a major feeding area for bowheads, so one area of emphasis was the feeding behavior of the animals and the characteristics of their feeding locations.

6. The principal objective of the project was an analysis of the effects, on bowheads, of offshore industrial activities in the Beaufort Sea. The studies of normal behavior, feeding areas and industrial noise were included to provide information relevant to the central question of disturbance effects.

7. It was assumed that sound would likely be an important mode of communication among bowheads, and that waterborne industrial sounds would likely be the most important type of disturbing stimulus. Thus monitoring of bowhead sounds, assessment of their behavioral

significance, and monitoring and analysis of industrial sounds were all considered to be important.

8. It was assumed that responses to disturbance might differ from normal behavior primarily in terms of the relative frequencies or durations of various behavioral acts, and not necessarily in any qualitative way. Thus, the studies of both normal behavior and disturbance responses needed to be systematic and quantitative. Disturbance experiments needed to be well controlled and replicated.

9. It was assumed that individual bowheads would be engaged in a variety of normal behaviors when encountered, and that responses to a particular type of boat, aircraft or noise disturbance would likely depend on the pre-existing behavioral and other circumstances. Thus, the experimental protocol for each disturbance trial needed to include observations during pre-disturbance control and, if possible, post-disturbance recovery periods as well as during the disturbance period itself. In this way, each animal or group would serve, in part, as its own control, and circumstance-dependent variability in responses would be at least partially taken into account.

Bases for Observation

We decided that three types of 'platforms' were necessary: aircraft, boats and shore camps. By using these platforms in a coordinated and complementary way, it was possible to maintain flexibility and redundancy, and to use the advantages of one or two platforms to counteract the disadvantages of the other(s). Table 1 summarizes the main strengths and weaknesses of the three platforms.

Because of their high mobility and good vantage point, **aircraft-based observers** have the best potential for locating whales quickly. They can make visual observations of the normal behavior of whales, deploy sonobuoys to monitor whale and industrial sounds in the water, and observe reactions of the whales to an approaching boat or, in a limited way, the aircraft itself.

Table 1. Strengths and weaknesses of aircraft, boats and shore camps as observation platforms.

	Aircraft	Boats	Shore camps
Mobility	Good	Moderate	Poor
Vantage Point	Good	Poor	Moderate
Stability	Poor	Moderate	Good
Sound recording			
sonobuoys	Yes	Yes	Yes
suspended hydrophone	No	Yes	Yes
bottom hydrophone	No	Possible	Yes
Sound playback			
suspended projector	No	Yes	Yes
bottom projector	No	Possible	Yes
Ability to sample the water	No	Yes	via small boat

Aircraft-based observers are also able to direct a boat toward whales when the boat-based observers cannot see the whales.

Boat-based observers have the disadvantages of only limited mobility and a poor vantage point for observations. However, unlike aircraft-based observers, they have capabilities for marine sampling and for creating underwater sounds. Furthermore, the boat is an integral component of the boat disturbance trials.

Shore-based observers have the major disadvantage of limited mobility. They depend, for the most part, on the assumption that whales will come close to shore at one or more preselected sites where there is a high vantage point. The advantage of shore-based observations, assuming that whales do approach the vantage point, is that a greater variety of observational methods are possible from shore than from aircraft or boats (Table 1). Only from shore can one apply the transit method for recording the movements and behaviors of whales. This method provides precise time-series data on the locations, speeds, turns and behaviors of whales, and is of special value in a systematic disturbance study involving alternating control and disturbance periods (Clark and Clark 1980). A further and major advantage of shore-based observations is that the observers are less likely to disturb the whales than is the case with boat- and aircraft-based observations.

Based on the above considerations, it was obvious that both aircraft and boat-based work were essential, and that shore-based work was also highly desirable if suitable locations could be identified. Suitable coastal locations would be those where there is (1) a high vantage point, and (2) a high probability that bowheads will be seen. Based on the limited previous information (Fraker and Bockstoce 1980), two such sites were identified during the planning for this study: along the east coast of Bathurst Peninsula in early and mid summer, and along the north coast of the Yukon Territory in late summer. The Yukon coast was selected as the best choice for shore-based work in both 1980 and 1981.

Task-by-Task Design

On a task-by-task basis, the general design of the study was as follows:

1. **Normal behavior task.** It was assumed that aircraft-based observers would be able to find bowheads regularly and, by remaining at an altitude of at least 300 m, would be able to observe their normal behavior without causing serious aircraft disturbance. (In fact, it proved necessary to remain at or above 450 m.) The plan was to circle high above one or more whales for an hour or more, dictating into tape recorders information about the time series of dives, surfacings, respirations, orientations, turns, feeding, interactions, inter-whale distances, aerial behavior (breaching, fluking, flipper-slapping), etc. These data would serve as the basis for quantitative analyses of the frequency, context and characteristics of these behaviors. A video camera was to be used to provide a permanent record of bowhead behavior. This approach worked well in both years.

It was assumed that boat-based observers would collect similar data, but that their capabilities would be hindered by difficulties in finding bowheads, by the low vantage point afforded by a rather small boat, and possibly by the disturbing effect of the boat.

It was hoped that bowheads would approach the shore camps; if they did so, similar types of data could be obtained for nearshore areas. Also, more detailed information about movements, including speeds, would be obtained using the transit method.

Observers on each of the three types of 'platforms' were equipped to listen to and record bowhead sounds. It was hoped that different sound types could be related to the overall behavioral context. To assist in this task, a directional hydrophone array similar to that of Clark (1980) was built for use at the shore camp. The inability to determine the bearing (and hence the specific whale) from which a sound is coming has been a main limitation in many previous studies of the context of whale sounds. We hoped to use the directional array to minimize this problem, but were unsuccessful because of the rarity with which bowheads approached shore in 1980 or 1981.

2. **Boat and Aircraft Disturbance Trials.** Boat disturbance trials were to be conducted via coordinated use of a boat and the aircraft. Observers were to be present on both platforms, but the aircraft-based observers were expected to have the better view. The plan for each trial was (a) to observe undisturbed behavior for at least 15-30 min, (b) then to move the boat past the whales at a lateral distance of about 500 m (in the initial series of trials) and continue to observe from the air and the boat, and (c) to continue aerial observations for at least 15-30 additional minutes. Behavioral parameters to be monitored would be the same as those listed above under 'Normal Behavior'. Sonobuoys would be deployed to monitor bowhead and boat sounds. It was hoped that additional data about boat disturbance would be obtained opportunistically by boat-based personnel in the absence of the aircraft. To ensure that the aircraft and boat could be closely coordinated, precise navigational equipment was needed on each. The aircraft was equipped with a Very Low Frequency (VLF) navigation system, and a Navigation Satellite receiver was used on the boat.

Aircraft disturbance trials of a variety of types were planned. The intent was to quantify the reactions of bowheads to overflights at various altitudes. The simplest approach envisaged was to observe from the disturbing aircraft itself. Shore-based observations of reactions to overflights were planned if bowheads approached shore regularly, and boat-based observations were planned if it proved impractical to obtain the needed data from shore and aircraft. In practice, the aircraft- and shore-based approaches were used, and underwater sounds below various aircraft were recorded and studied.

3. **Responses to Noise.** Shore-camps provided the best potential for detailed noise-playback experiments, but we also were prepared to conduct playbacks from the seagoing boat. Underwater sound projectors were available for use from both shore and the boat. In 1981, we also obtained an airgun for use as a simulated source of seismic survey signals. The planned procedure was analogous to that for the boat-disturbance trials. For each of several replicated trials, there would be a pre-playback period of control observations, a playback period, and a post-playback recovery period. This approach has been employed successfully by Clark and Clark (1980) during playback experiments on southern right whales. In practice, the limited number of opportunities for playback work were devoted to experiments with the airgun.

Supplementary information about noise characteristics and effects was to be gathered by recording waterborne sounds at various distances from industrial sources in the eastern Beaufort Sea (seismic ships, drillships, dredges, etc.), observing the behavior of any bowheads seen near ongoing offshore exploratory activities, and collecting observations by industry personnel of bowheads near such activities.

4. **Characteristics of Feeding Areas.** The main components of this task were to sample zooplankton and to measure temperature and salinity profiles at places where bowheads were observed to feed, and at a limited number of other places. A drop-net system for sampling mobile epibenthic invertebrates was also provided. In 1981, we also used an echosounder to help locate concentrations of zooplankton. The equipment was to be deployed primarily from the seagoing boat. Limited additional capabilities for nearshore sampling from an inflatable boat were provided.

IMPLEMENTATION OF PLANS

A specially-equipped Britten-Norman Islander outfitted and operated by NORCOR Engineering and Research, Ltd., was selected for aerial observations over offshore waters. This aircraft was used for 5 weeks in 1980 and 6.5 weeks in 1981. The Islander is a high-wing aircraft with two piston engines, low stall speed, and other STOL (Short Take Off and Landing) characteristics. The NORCOR Islander was equipped with a VLF navigation system for precise position-finding, radar altimeter, forward-looking radar that could be used to measure distances to large objects (e.g. drillships), long-range fuel tanks, and other specialized equipment. Sonobuoys could also be deployed and monitored from the Islander.

Because the contract was not awarded until 30 June 1980, arrangements for boat charters in 1980 were less than ideal, and the boat-based operations in 1980 were not very efficient. Nonetheless, some useful data were obtained. In 1981, a more suitable vessel was chartered for the full 6.5 week field period.

Shore camps were established at two locations along or near the Yukon coast from mid-August to mid-September in both years. Useful data concerning normal behavior of bowheads were obtained from a site on the eastern end of Herschel Island. However, bowheads were rarely seen near the second site, which was at King Point along the mainland coast of the Yukon (see Fig. 1 for locations).

The methods and results are described in four self-contained but complementary sections of this report:

-Normal behavior of bowheads (Würsig et al. 1982);
-Disturbance responses of bowheads (Fraker et al. 1982);
-Characteristics of waterborne industrial noise (Greene 1982); and
-Characteristics of bowhead feeding areas (Griffiths and Buchanan 1982).

These four sections are summarized below.

SUMMARY OF RESULTS

This study was not designed to document the distribution and movements of bowheads in the eastern Beaufort Sea. However, limited distributional information was gathered, and this is of some relevance in assessing the behavioral results. (Separate detailed distributional studies were done in both 1980 [Renaud and Davis 1981] and, on a wider scale, in 1981 [Davis et al. 1982].)

The distribution and activities of the whales differed between 1980 and 1981. In August 1980, bowheads were common in shallow water (10-30 m) just off the Mackenzie Delta (especially in early-mid August) and the Tuktoyaktuk Peninsula (especially in late August). The main activity of these whales was feeding. In 1981, most bowheads found in early August were far offshore, near the edge of the continental shelf. These whales were also near or in the pack ice, whose southern border was near the edge of the shelf in early August. By mid August of 1981, some bowheads had moved into somewhat shallower water closer to shore, but the whales remained farther offshore throughout August than had been true in 1980. Preliminary results from August 1982 show that bowhead distribution then was different from that in both 1980 and 1981 (LGL Ltd., unpubl. data).

In both 1980 and 1981, some bowheads approached within a few kilometres of the northeastern shore of Herschel Island, off the Yukon coast, in early September. However, contrary to the situation in some recent years (cf. Fraker and Bockstoce 1980), bowheads rarely approached the mainland coast of the Yukon in late August or early September.

Normal Behavior of Bowheads

The report with the above title (Würsig, Clark, Dorsey, Fraker and Payne 1982) describes the 'undisturbed' behavior of bowhead whales summering in the southeastern Beaufort Sea. Feeding, travelling and socializing were the main activities of the whales. However, relatively inactive individuals were occasionally seen, especially in areas with brash or pan ice. Much of the following summary is taken from the Abstract of the report by Würsig et al.

Behavior of bowhead whales was observed from an aircraft during 14 of 16 flights on 3-31 August 1980 and 18 of 28 flights on 31 July-8 September 1981, mostly off the Tuktoyaktuk Peninsula and Mackenzie Delta, N.W.T., Canada. Excluding ferry and reconnaissance time, detailed behavioral observations were made for 30.4 h in 1980 and 30.8 h in 1981, while flying distances up to approximately 200 km from home base at Tuktoyaktuk. Observations obtained when the behavior of the whales may have been affected by proximity to industrial activities, or by our activities, were not used in assessing normal 'undisturbed' behavior.

Feeding. -- During 1980, the predominant activity seen was feeding. At various times bowheads apparently fed in the water column, at or near the bottom, and at the surface. An additional behavior, 'mud tracking', also seemed to be associated with feeding. Underwater blows also tended to occur during periods of feeding, but there was no definite evidence that they were a feeding behavior. All five of these behaviors were seen less frequently in 1981, and mud tracking was not seen at all.

Water-column feeding could not be observed directly, and it was not always possible to determine whether the whales were feeding below the surface. However, series of long dives separated by surfacings with much defecation and only slow forward motion were considered indicative of probable water-column feeding. This behavior was seen frequently from 3 to 22 August 1980, but rarely thereafter or in 1981.

Near-bottom feeding was evident when whales surfaced with large streams of muddy water emanating from their mouths. This was seen on three days in 1980, in water 24-29 m deep, and on one day in 1981, in water only 10-13 m deep. We suspect that these bowheads had fed near the bottom on epibenthic animals rather than on inbenthos.

Skim feeding at or near the surface with mouths wide open was observed directly in 1980 and, less frequently, in 1981. Whales sometimes skim fed alone, but more often did so in well organized groups of 2 to 14 individuals. These groups were in echelon formation, each whale swimming beside and slightly behind the preceding one. On one occasion when detailed sampling of plankton was possible amidst whales engaged in prolonged and extensive echelon feeding just below the surface, copepods were unusually abundant in near-surface waters.

'Mud tracking' occurred in 1980 when whales in only 10-12 m of water stirred up mud as they moved along below the surface. This movement sometimes left a trail of mud over 1 km long. Underwater exhalations often occurred during mud tracking, but were also seen at other times.

Social interactions -- nudges, pushes, chases, and close proximity--were observed less often than feeding in 1980, but fairly often in 1981. During both years social behavior was less predominant in late August-early September than in early August. The diurnal peak in socializing was from 14:00-16:00 MDT, which bridges sidereal noon. No sexual interactions were recognized in 1980, but two apparent sexual interactions were witnessed in 1981. In 1980, there were a few displays of aerial activity (breaches, tail slaps, flipperslaps, and associated activity at the surface), mainly by lone whales, but in 1981 aerial activity was more often associated with socializing whales. On two occasions in 1981 whales were observed playing with logs floating at the surface.

Synchrony. -- Different bowheads, at times spread over tens of km^2, tended to be engaged in the same activity and to assume similar orientations, even when apparently not migrating. The timing of surfacings and dives sometimes seemed to be synchronized over a large area, but this was not substantiated by statistical analysis of the limited data concerning this point. The consistency in orientations was often strong; during 10 of 14 flights orientations of whales were significantly different from random. However, orientations changed between days. It is not known whether consistencies in orientation were attributable to social synchrony or to independent reactions to environmental stimuli, such as currents or wave patterns.

Individual recognition. -- A few individuals were readily recognizable by distinctive features such as unusual white pigmentation or, in one case on 3 August 1980, a harpoon line. In 1980, one group consisting of two distinctively marked large whales and a calf was resighted after 2 weeks. In addition, detailed observations with binoculars often allowed identification of subtle and small marks on the backs of bowheads, and this allowed us to identify individuals for brief periods during particular observation sessions. Our experience and work by Davis et al. (1982) show that a concerted effort to identify individuals from good aerial photographs would be successful.

Surfacings, respiration and dives. -- Intervals between blows, number of blows per surfacing, durations of surfacings, and durations of dives were measured 2067, 270, 319 and 115 times, respectively, for whales that were apparently undisturbed. The variability (day-to-day and hour-to-hour) in the number of blows per surfacing and the duration of surfacing was greater than the variability in interval between blows. Overall, blow intervals within single surfacings averaged 13.0 ± s.d. 8.38 s. The mean number of blows per surfacing was 4.19 ± s.d. 2.90, and the overall mean duration of each surfacing was 1.09 ± s.d. 0.79 min. The number of blows per surfacing and duration of surfacing were highly correlated. The overall mean duration of dives by recognizable whales was 3.17 ± s.d. 4.535 min. This estimated mean is undoubtedly biased and too low; it was easier to time short than long dives. The longest recorded dive by a presumably undisturbed whale lasted 17.42 min. A potentially disturbed whale dove for 26.8 min.

Several factors were related to respiration rate and to the durations of surfacings and dives. Long dives, during which the whales were often believed to be water-column feeding, tended to be followed by long surfacings with many respirations per surfacing. However, whales did not blow at briefer intervals after long dives. Females with calves respired less often than their calves and other adults, suggesting a lower activity level by the maternal females. Socializing whales also respired less often than whales otherwise engaged. This result may be due in large part to the fact that dives of socializing whales tended to be shorter than dives of non-socializing whales.

Calves were slightly more than one-half the length of accompanying adults, and they were usually close to the side of the presumed mother. However, calves were on one occasion seen 100-300 m from adults, apparently remaining at the surface while adults dove. On 8 September 1981, a calf breached repeatedly while moving away from the accompanying adult, separating the two by about 1 km at one point.

Calls. -- Analysis of recordings made via sonobuoy distinguished approximately 9 bowhead call types, with the principal distinguishing feature being the frequency sweep of the call. Call types were similar to those off Point Barrow, Alaska, in spring, but the relative proportions of the call types differed between the two areas. Whales which were resting, swimming, or feeding made mostly frequency modulated calls, usually at a low rate. Actively socializing whales had a higher rate of sound production, and most of their calls were complex and pulsive. Bowhead and southern right whales have very similar call repertoires.

Excluding blow and slap sounds, 57% of the sounds were tonal FM calls--ascending, descending or constant in frequency. Most FM calls contained acoustic energy between 100 and 250 Hz, but some had frequencies 400-1200 Hz. Purr-like FM calls had fundamental frequencies of 30-110 Hz plus up to 16 harmonics. Pulsive calls contained broadband energy, principally at 400-2000 Hz.

Relationships to behavior in other species and areas. -- There was a strong overall resemblance between the behavior of bowhead and right whales, despite the fact that we observed bowheads in summer, whereas right whales have been studied mainly in winter. (Both species mate and calve in winter and feed primarily in summer.)

Bowhead behavior in our study area in summer appears similar to that in the Alaskan Beaufort Sea in autumn. Travelling is probably more prominent in autumn and feeding more prominent in summer, but both activities occur in both seasons. Behavior in spring is probably less similar, since--during spring migration--feeding is infrequent, travel is more directed, and ice is a major factor.

Disturbance Responses of Bowheads

The report with the above title (Fraker, Richardson and Würsig 1982) describes the behavior of bowhead whales in the presence of actual or simulated industrial activities associated with offshore oil and gas exploration and development. The report presents data concerning responses to boats, aircraft, noise from seismic exploration, dredging and drillships. Both observational and experimental results were obtained for boats, aircraft and seismic noise; only observational results were obtained for dredging and drillships.

The experimental and observational approaches were complementary. (1) The experimental approach, in which we observed one or more whales before, during and often after a period of simulated industrial activity, provided control data from the same animals as were exposed to the industrial activity. This greatly facilitated detection of disturbance effects. (2) When we observed whales near ongoing industrial activities, pre-disturbance data from the same whales generally were not obtainable. However, these observations near full-scale industrial operations had the advantage of realism (in terms of both magnitude and duration), which we could not simulate adequately in brief experiments.

Most of the behavioral observations near real or simulated industrial activity were obtained from the Islander aircraft circling high overhead. Industrial and whale sounds during experiments and other observation sessions were monitored via sonobuoys dropped from the aircraft. More detailed information about waterborne industrial sounds was obtained by hydrophones deployed from boats.

We observed reactions of bowheads to close approach by **boats** or small ships on four occasions. In each case, observations were obtained before the boat approached as well as near the time of closest approach. Bowheads responded in two main ways: (1) When boats were nearby, bowheads altered their surfacing and diving pattern by decreasing the mean time at the surface per surfacing, the mean number of blows per surfacing, and the mean dive duration. Mean surface times and blows/surfacing were reduced even in response to a stationary 16 m boat with its engines idling at a range of 3-4 km. (2) When boats closed to within 1-3 km, the whales, in addition to the above responses, swam rapidly away from the boat and scattered. Whales directly on the boat's track initially tried to outrun it, but usually turned to move off the track as the boat closed to within a few hundred metres. None of the boat disturbances that we observed resulted in the whales' leaving an area; however, the effects of more frequent boat disturbance are unknown. Reactions to boats were stronger in the case of summering bowheads (this study) than in the case of summering gray whales (LGL unpubl.).

Bowheads typically dove in response to our Islander observation **aircraft** when it circled above the whales at ≤305 m above sea level (ASL). They occasionally dove in response to the aircraft when we circled at 457 m. Considering all data collected in 1980-81, mean surface times were slightly reduced when the aircraft circled at 457 m relative to those when it circled at 610 m, but there was no evidence of an effect on respiration or dive characteristics. On two days when a group of whales was circled at 610 m and then at 457 and/or 305 m, there were clear effects on respiration when the aircraft descended. In general, reactions to a circling aircraft were conspicuous if it was at 305 m, minor at 457 m, and absent or undetectable at 610 m.

Underwater noise from a Bell 212 helicopter was stronger than that from the Islander. Thus, reactions of bowheads to such a helicopter would probably be stronger than those to the Islander. However, during straight-line passes at 152-610 m ASL over a hydrophone, helicopter sound was detectable for only 16-27 s.

Noise from **seismic exploration** is by far the most intense noise in the Beaufort Sea, although it is not continuous. In 1980 and 1981 we saw bowheads as close as 13 and 6-8 km, respectively, from a seismic ship that was firing 12 large sleeve exploders. Seismic signal levels at those ranges were 141 and 150 dB//1 μPa. Surfacing and respiration behavior at 13 and 8 km from the seismic ship was similar to that at corresponding water depths in the absence of seismic noise. Industry personnel reported sightings of bowheads 2-7 km from a seismic ship that uses airguns. Sonobuoys showed that bowheads often continued to call in the presence of seismic noise.

Bowheads may react more strongly at the onset of seismic exploration. During a controlled experiment with one 40 in^3 (655 cm^3) airgun 5 km from bowheads engaged in echelon-feeding, we found significantly reduced surface times, blows/surfacing and calling rate, and possibly reduced dive times and echelon sizes. The airgun was fired every 10 s for 20 min, and near the whales the signal level from the airgun was at least 123 dB//1 μPa. No unambiguous behavioral effects were demonstrated during a second airgun experiment 3 km from whales, and there was circumstantial evidence of habituation to seismic noise. The source level of noise from arrays of airguns used in full-scale seismic exploration can be about 25 dB higher than that from our single airgun (248 vs. 222 dB//1 μPa at 1 m). If bowheads react to the onset of noise from one airgun 5 km away, as our results suggest, they can be expected to react to the onset of full scale seismic operations 20 km away in our shallow study area, and possibly farther away in a deeper area where sound propagation is better.

In 1980, bowheads frequently were seen <5 km from an artificial island that was under construction by a **dredge**; LGL personnel saw bowheads as close as 800 m from the operation, and industry personnel reported that one bowhead came as close as 16 m from a barge near the dredge site. Sounds from the dredge were well above ambient levels, and almost certainly audible to bowheads, out to at least 7.4 km.

We obtained only limited information about behavior of bowheads near sites of offshore **drilling**, and this drilling was from drillships, not from islands. We saw bowheads as close as 4 km from a **drillship**, and industry personnel reported closer sightings. The strongest tonal sound from the drillship (278 Hz) was about 111 dB//1 μPa at 4 km from the ship. It is uncertain whether bowhead behavior was affected by the presence of the drillship. Respiration and diving behavior 4 km from the drillship differed from that in its absence, but also differed from behavior with boat or airgun disturbance.

Characteristics of Waterborne Industrial Noise

The report with the above title (Greene 1982) documents the characteristics of the underwater sounds to which bowhead whales were exposed during the experiments and observations summarized above. Underwater noise from certain other industrial sources, including a hopper dredge, a Twin Otter aircraft, and a Bell 212 helicopter, also was studied. In addition, the rate of attenuation of several types of industrial sounds with increasing distance from their sources was analyzed. The results are presented in four main ways: (1) averaged power spectra to describe the average characteristics of industrial machinery sounds, (2) spectrograms to describe the temporal behavior of industrial machinery sounds, (3) pressure-time waveforms to describe seismic survey sounds, and (4) equations for received level vs. range to describe the propagation of important components of sounds from in-water sources.

Velocity profile. -- All work was in the open water of the eastern Beaufort Sea generally north of Tuktoyaktuk during August of 1980 and 1981. The shallow water varied in depth between 11 and 50 m. Measured salinity-temperature-depth data yielded profiles of the sound speed vs. depth. Sound speed was relatively constant from the surface to 8 or 10 m, decreased steeply from there to about 20 m, and was then constant to the bottom. Such a sound speed structure in such shallow water assures that sound will travel via downward refracted rays that bounce repeatedly between the surface and the bottom. Higher frequencies will be scattered and absorbed, and lower frequencies will not propagate significantly in the shallow water.

Ships and boats whose sounds were studied were a sea-going hopper dredge, two small supply ships, a personnel support boat, and the fishing boat used to collect many of the sound data. The hopper dredge 'Geopotes X', 136 m in length and displacing 17,981 tons, radiated the strongest signal component, a tone varying in frequency between 70 and 92 Hz. The received level was 138 dB//1 μPa at 460 m and is predicted to be 146 dB at 100 m, based on a regression equation relating received level to range; this equation was derived from measurements at ranges between 0.46 and 7.4 km. The dominant tone from a supply ship underway was at 56 Hz. It was measured at an estimated range of 185 m as 121 dB//1 μPa, and would be expected (based on regression estimates for other sounds) to be about 124 dB//1 μPa at 100 m. The bow thruster on another supply ship measured at 185 m radiated a strong harmonic family of tones whose fundamental frequency was at 118 Hz and whose strongest member was the second harmonic with an expected level at 100 m of 132 dB//1 μPa. The highest frequency tone found consistently was at 1000 Hz and came from the hopper dredge; its level at 100 m would be expected to be 130 dB//1 μPa.

Aircraft noise. -- The fundamental propeller blade-rate from a Britten-Norman Islander twin-engine aircraft at 152 m ASL (500 ft) occurred at 70 Hz at a level of 100-102 dB//1 μPa, measured at 18 m depth and averaged over 4 s. The strongest tone from a deHavilland Twin Otter at 152 m occurred at 82 Hz at a level of 104-110 dB//1 μPa, also averaged over 4 s but measured at 9 m depth. The strongest recorded tone from a Bell 212 twin-turbine helicopter occurred at 22 Hz at a level of 109 dB//1 μPa, measured at 9 m depth and averaged over 4 s. During the 1 s period of peak noise, the overall broadband helicopter sound was more intense than that from the two fixed-wing aircraft, and the level decreased with increasing altitude. However, when averaged over 8 s or 4 s, aircraft noise was not closely related to altitude. When the Twin Otter or Bell 212 helicopter flew over a hydrophone in water 22.5-25 m deep under low sea state conditions, the aircraft sound was audible for 16-37 s, depending on aircraft type and altitude.

Seismic exploration. -- In terms of intensity, the sleeve exploder signals from a seismic survey ship were much stronger than any other sounds examined in this study. They consisted of a series of high intensity pulses separated by several seconds. The length of the signal was 250 ms when received at 8 km and 400 ms at 28.7 km. The effect of the sound transmission properties existing during the measurements (which were typical for the place and season) was to stretch the signal from the impulse present at the source into a chirp-like signal descending in frequency at ranges beyond about 5 km. Signatures from an airgun were chirp-like at 5 but not at 3 km. A regression equation for received level of the sleeve exploder signals vs. range, derived from the measured signatures at 8-28.7 km ($R^2 = 0.97$, $n = 12$), predicts a level of 180 dB//1 μPa at 100 m for frequencies near 150 Hz. This theoretical level is useful as an indication of the very high level of these signals relative to those from other sources. However, the actual level at such short range could be substantially different because of the extreme extrapolation involved (the closest range at which measurements were taken was 8 km). At the longest ranges studied (28.7 km), the sleeve exploder signature 'chirped' from about 200 Hz down to 100 Hz, indicating that this range of frequencies probably propagates best in shallow waters of the eastern Beaufort Sea. That is also the frequency range of many of the bowhead calls.

Drillship and dredge sounds were continuous during the periods of measurement, but not always very stable in their characteristics. The dominant tonal component in the drillship signature was at 278 Hz (evidently from the main power plants) at a predicted level of 133 dB//1 μPa at 100 m. The dominant dredge tone was at 380 Hz and its predicted level at 100 m was 120 dB//1 μPa.

Transmission loss was examined using the equations fitted to received signal levels vs. range. These equations revealed that a cylindrical spreading term (10 log R) plus an absorption loss term (linear function of R) provide a good description of received levels. The absorption loss term is frequency dependent but insufficient data prevent us from determining the exact form of the relationship. The absorption loss term for one type of signal at 80 Hz was 0.17 dB/km, and that for another type of signal at 1000 Hz was 2.53 dB/km. However, the results at middle frequencies were inconsistent.

Characteristics of Bowhead Feeding Areas

The report with the above title (Griffiths and Buchanan 1982) documents the zooplankton composition and biomass in locations where bowheads were and were not observed. Water temperature and salinity were measured in relation to depth and area, and limited information on epibenthic animals was also obtained.

Physical measurements from both years revealed two distinct water layers in the nearshore shallow water region where bowheads were feeding during August--(1) a warm and brackish surface layer, generally at depths 0 to 7.5-15 m, and (2) a colder and more saline layer below. Within the general feeding area, no differences were evident in either year between the temperature and salinity profiles in locations where bowheads were and were not observed. Waters in the general study area appeared to be a few parts per thousand (ppt) less saline in 1981 than in 1980. Vertical **zooplankton** hauls taken off Richards Island, N.W.T., and King Point, Y.T., in 1980 showed that hydrozoans and copepods were the dominant groups in terms of biomass (range for total biomass: 1302-12 mg/m^3 wet wt). Horizontal zooplankton tows taken off Tuktoyaktuk and Richards Island in 1981 also showed that copepods and hydrozoans were the dominant groups, in terms of biomass, with a minor contribution from amphipods (range for total biomass: 2456-0.06 mg/m^3 wet wt). Highest biomasses typically occurred below the thermocline (10 m and deeper) and usually were found just above the bottom. In both 1980 and 1981, five species of hydrozoans (Halitholus cirratus, Euphysa flammea, Sarsia princeps, Aglantha digitale, Aeginopsis laurentii) and five species of copepods (Calanus hyperboreus, C. glacialis, Limnocalanus macrurus, Pseudocalanus minutus, Derjuginia tolli) accounted for most of the biomass. However, the copepods contain much more energy per gram of wet weight. Drop net samples of **epibenthos** collected from three stations suggest that mysids (Mysis litoralis), isopods (Saduria entomon) and to a lesser extent copepods and hydrozoans comprised almost all the biomass on or near the bottom (1980: 1313-424 mg/m^2 wet wt.; 1981: 350 mg/m^2 wet wt.).

The results from both 1980 and 1981 suggest that bowhead whales tend to occur at locations with a significantly higher biomass of copepods than present in surrounding areas. In 1981, when bowheads were observed feeding at or near the surface, horizontal tows showed copepod biomass near the surface to be an order of magnitude greater in those areas than where whales were not observed.

The average zooplankton biomass found in areas where bowheads were observed was 0.558 g/m^3 wet weight in 1980 and 0.449 g/m^3 wet weight in 1981. If bowheads are to consume their estimated daily caloric requirement each day, they must feed on aggregations of zooplankton that contain a somewhat larger average biomass than was found in either 1980 or 1981. Observations during this study ('Normal Behavior' section, Würsig et al. 1982) suggest that bowheads get portions of their daily food requirement (1) from surface waters, (2) from the water column, and (3) near or at the bottom. The abundance of hydromedusae within the areas where bowheads feed suggests that these animals are an important part of the bowhead diet even though they have not been reported in bowhead stomach contents.

During the open water season, bowheads travel from the Bering Sea to the Beaufort Sea. Annual primary production and zooplankton biomass are higher in the Bering Sea, and in addition the turnover rate of carbon is faster in the Bering Sea. A detailed cost/benefit analysis for the migration would have to consider seasonal variation in zooplankton biomass in each area, effects of depth and plankton patchiness on food availability in each area, the energy cost of swimming, and the effects of different thermal regimes. Available data are inadequate for such an analysis. However, the generally greater productivity of the Bering Sea suggests that factors unrelated to the total amounts of food in those two areas may cause bowheads to move into the Beaufort Sea in summer.

Neither this study nor any other has investigated the overall distribution, biomass and productivity of plankton in the eastern Beaufort Sea in a systematic or quantitative way. This type of information would be needed to assess the effects of the potential exclusion, by industrial activity, of summering bowheads from certain feeding areas. As yet, it is uncertain whether such exclusion would actually occur, but the demonstrated reactions to boats, aircraft and the start-up of seismic exploration suggests that the possibility is real, at least on a local basis. The importance of exclusion from specific areas with intense industrial activity would depend on food availability there and elsewhere. In particular, the availability of unexploited 'patches' of concentrated food in alternate areas would be important if bowheads were excluded from favored areas. Neither the occurrence nor the factors controlling plankton patchiness has been studied in the eastern Beaufort Sea.

Distributional studies in 1980-1982 have shown considerable year-to-year variability in the movements and concentration areas of summering bowheads. It is not known whether there were corresponding variations in food availability. This uncertainty confounds any attempt to relate changes in bowhead activities to changes in industrial activity. This study has shown that bowheads sometimes show pronounced short-term reactions to transient industrial activities such as boats, aircraft and start-up of seismic sounds. However, bowheads also show considerable tolerance of ongoing activities such as dredging, drilling and prolonged seismic exploration. Whether any of the year-to-year variations in distribution can be attributed to these industrial activities is unknown.

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NORMAL BEHAVIOR OF BOWHEADS*

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* Würsig, B., C.W. Clark, E.M. Dorsey, M.A. Fraker and R.S. Payne. 1982. Normal behavior of bowheads. p. 33-143 *In*: W.J. Richardson (ed.), Behavior, disturbance responses and feeding of bowhead whales *Balaena mysticetus* in the Beaufort Sea, 1980-81. Chapter by New York Zool. Soc. in unpubl. rep. from LGL Ecol. Res. Assoc., Inc., Bryan, TX, for U.S. Bureau of Land Management, Washington. 456 p.

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ABSTRACT

Behavior of bowhead whales was observed from an aircraft during 14 of 16 flights on 3-31 August 1980 and 18 of 28 flights on 31 July-8 September 1981, mostly off the Tuktoyaktuk Peninsula and Mackenzie Delta, N.W.T., Canada. Excluding ferry and reconnaissance time, detailed behavioral observations were made for 30.4 h in 1980 and 30.8 h in 1981, while flying distances up to approximately 200 km from home base at Tuktoyaktuk. During 1981, whales were, in general, less concentrated and farther from shore than in 1980.

During 1980, the predominant activity seen was feeding. At various times bowheads apparently fed in the water column, at or near the bottom, and at the surface. An additional behavior, 'mud tracking', also seemed to be associated with feeding. Underwater blows also tended to occur during periods of feeding, but there was no definite evidence that they were a feeding behavior. All five of these behaviors were seen less frequently in 1981, and mud tracking was not seen at all.

Social interactions--nudges, pushes, chases, and close proximity--were observed less often than feeding in 1980, but fairly often in 1981. During both years social behavior was less predominant in late August-early September than in early August. The diurnal peak in socializing was from 14:00-16:00 MDT, which bridges sidereal noon. No sexual interactions were recognized in 1980, but two apparent sexual interactions were witnessed in 1981. In 1980, there were a few displays of aerial activity (breaches, tail slaps, flipperslaps, and associated activity at the surface), mainly by lone whales, but in 1981 aerial activity was more often associated with socializing whales. On two occasions in 1981 whales were observed playing with logs floating at the surface.

Different bowheads, at times spread over tens of km^2, tended to be engaged in the same activity and to assume similar orientations, even when apparently not migrating. The timing of surfacings and dives sometimes seemed to be synchronized over a large area, but this was not substantiated by statistical analysis of the limited data concerning this point. The consistency in orientations was often strong; during 10 of 14 flights orientations of whales were significantly different from random. However, orientations changed between days. It is not known whether consistencies in orientation were attributable to social synchrony or to independent reactions to environmental stimuli, such as currents or wave patterns.

A few individuals were readily recognizable by distinctive features such as unusual white pigmentation or, in one case on 3 August 1980, a harpoon line. In 1980, one group consisting of two distinctively marked large whales and a calf was resighted after 2 weeks. In addition, detailed observations with binoculars often allowed identification of subtle and small marks on the backs of bowheads, and this allowed us to identify individuals for brief periods during particular observation sessions.

Intervals between blows, number of blows per surfacing, durations of surfacings, and durations of dives were measured 2067, 270, 319 and 115 times, respectively, for whales that were apparently undisturbed. The variability (day-to-day and hour-to-hour) in the number of blows per surfacing and the duration of surfacing was greater than the variability in interval between blows. Overall, blow intervals within single surfacings averaged 13.0 ± s.d. 8.38 s. The mean number of blows per surfacing was 4.19 ± s.d. 2.90, and the overall mean duration of each surfacing was 1.09 ± s.d. 0.79 min. The number of blows per surfacing and duration of surfacing were highly correlated. The overall mean duration of dives by recognizable whales was 3.17 ± s.d. 4.535 min. This estimated mean is undoubtedly biased and too low; it was easier to time short than long dives. The longest recorded dive by a presumably undisturbed whale lasted 17.42 min. A potentially disturbed whale dove for 26.8 min. There was no consistent relationship between time of day and any of the respiration and surfacing characteristics.

Several factors were related to respiration rate and to the durations of surfacings and dives. Long dives, during which the whales were often believed to be water-column feeding, tended to be followed by long surfacings with many respirations per surfacing. However, whales did not blow at briefer intervals after long dives. Females with calves respired less often than their calves and other adults, suggesting a lower activity level by the maternal females. Socializing whales also respired less often than whales otherwise engaged. This result may be due in large part to the fact that dives of socializing whales tended to be shorter than dives of non-socializing whales. Surface times, blows per surfacing and dive times tended to be short when water depth was very shallow (≤15 m), but otherwise there was no clear relationship between these variables and water depth.

Calves were slightly more than one-half the length of accompanying adults, and they were usually close to the side of the presumed mother. However, calves were on one occasion seen 100-300 m from adults, apparently remaining at the surface while adults dove.

Analysis of recordings made via sonobuoy distinguished approximately 9 bowhead call types, with the principal distinguishing feature being the frequency sweep of the call. Call types were similar to those off Point Barrow, Alaska, in spring, but the relative proportions of the call types differed between the two areas. Whales which were resting, swimming, or feeding made mostly frequency modulated calls, usually at a low rate. Actively socializing whales had a higher rate of sound production, and most of their calls were complex and pulsive. Bowhead and southern right whales have very similar call repertoires.

In addition to aerial observations, shorebased observations using a theodolite were obtained in both years from Herschel Island, Yukon Territory, Canada. The mean water depth over which whales travelled near shore was 32.0 + s.d 10.24 m, n = 179, in 1980, and 36.3 ± s.d. 9.36 m, n = 78, in 1981. Blow intervals (14.6 ± s.d. 9.56 s, n = 60) were slightly longer than those seen from the air during the study as a whole. During 1980, the average swimming speed was 5.1 ± s.d. 2.93 km/h, n = 18. On 8 September 1981, a calf observed from shore breached repeatedly over a period of 20 min. Its average speed between breaches was 5.5 ± s.d. 3.98 km/h, n = 10, and it moved up to 22.7 km/h as it headed back to its presumed mother 1 km distant.

Ringed seals, white whales, phalaropes, and gulls at times were seen near bowhead whales. Birds may have been feeding on prey stirred up by the whales.

There was an overall strong resemblance between the behaviors of bowhead and southern right whales, despite the fact that we observed bowheads in summer and right whales in winter.

INTRODUCTION

The normal, undisturbed behavior of the bowhead whale, Balaena mysticetus, has not been the specific object of any previous study. Limited information about various aspects of its behavior has been obtained during several studies with more general objectives. The present study was conducted as part of a broader analysis of the potential effects, on bowheads, of offshore oil and gas exploration and development in the Beaufort Sea. In order to assess these effects, and in particular to plan and interpret experimental studies of the effects of industrial activities on behavior, it was necessary to obtain a more comprehensive and quantitative understanding of the normal behavior of the bowhead.

This 'normal behavior' study is one of several tasks comprising the overall study. The other tasks are studies of the responses of bowheads to boat, aircraft and noise disturbance (Fraker et al. 1982; Greene 1982) and a study of the characteristics of bowhead feeding areas (zooplankton, epibenthos, temperature, salinity, etc.; Griffiths and Buchanan 1982). The work on all tasks was planned as a two-year study and the present report presents final analyses of the results from these two years.

Objectives

The general rationale for the overall study is given in the preceding 'Project Rationale, Design and Summary' section (Richardson and Fraker 1982). The specific objectives of the 'Normal Behavior' task have been defined by the Bureau of Land Management in the following way:

-"Identify and describe, qualitatively and quantitatively, the daily and seasonal behavior (e.g., feeding, breeding and calving) and activity patterns of the various age and sex classes of bowhead whales that occur in the eastern Beaufort Sea, and as it relates to the U.S. Beaufort Sea lease sale area... .

-"Provide reliable baseline information which, in conjunction with long-term monitoring programs, can be used to detect changes in bowhead whale distribution, movements, activity patterns, etc. that may be caused by offshore oil and gas development in the Beaufort Sea.

-"Assist and coordinate with other BLM investigators in collecting information needed to: (a) determine the seasonal distribution and movements of bowhead whales in and adjacent to the Beaufort Sea Lease Sale Area; and (b) identify and characterize bowhead whale feeding areas, breeding/calving areas, or other areas of similar biological significance that may occur in or adjacent to the Beaufort Sea Lease Sale Area."

After discussions with BLM, it was agreed that our work should be in the eastern part of the Beaufort Sea, off Canadian shores, and that the studies of normal behavior should be oriented toward developing a general (as opposed to site-specific) understanding of bowhead behavior in the Beaufort Sea. Analysis of feeding, social and reproductive behavior and other general aspects of behavior were to be emphasized in this study, and studies of distribution and seasonal movements were to be de-emphasized*. General knowledge that could best be obtained during this study in the eastern Beaufort, together with results from site-specific studies of bowhead activities in and near the lease areas in the Alaskan Beaufort (e.g. Ljungblad et al. 1980b; Ljungblad 1981), would then be used to assess potential disturbance effects in the lease areas.

The underlying basis for this study is the concept that knowledge of normal behavior is a prerequisite for understanding the biological significance of responses to disturbance. It is widely assumed that waterborne sound is of great significance to marine mammals, and noise from offshore industrial activities has the potential to mask natural sounds or otherwise to disturb bowheads. Hence, an analysis of the characteristics and significance of bowhead calls is an important objective of the project.

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* Separately funded studies of distribution and movements of bowheads in the eastern Beaufort Sea were performed, however, in both 1980 (Renaud and Davis 1981) and 1981 (Davis et al. 1982).

Review of Previously Existing Knowledge

The behavior of bowhead whales has never been described in more than a general way. Fraker and Richardson (1980) summarize previous knowledge of the behavior of the bowhead. Scoresby (1820), Scammon (1874) and Bodfish (1936) discussed behavior of bowheads while the whales were under stress during capture, but systematic observations of undisturbed behavior commenced only recently. Davis and Koski (1980) and Koski and Davis (1980) measured durations of dives, surface times and swimming speeds for migrating bowheads in the eastern Canadian arctic. Braham et al. (1979), Rugh and Cubbage (1980) and Carroll and Smithhisler (1980) did similar work in the western arctic on whales migrating along the northwest coast of Alaska. Everitt and Krogman (1979) described six interacting whales during the spring migration past Point Barrow. One whale of this group had its penis extended, and the authors suspected that the group was involved in mating. There are other informal and anecdotal accounts of bowheads engaging in precopulatory behavior in the Bering and Chukchi Seas (e.g., Carroll and Smithhisler 1980; Johnson et al. 1981; Ljungblad 1981), and it is believed that mating occurs during the spring migration or just prior to it. During the present.study in the eastern Beaufort Sea during summer, much socializing and travelling and a small amount of apparent precopulatory activity were seen although, as hypothesized by Fraker and Bockstoce (1980), bowheads spent most of their time feeding.

Only in the last several years has there been reliable documentation of bowhead sounds, and no detailed analysis of those sounds has been published until very recently (see 'Bowhead Sounds' section, below).

The right whales (Eubalaena glacialis and E. australis) are the closest living relatives of the bowhead. Their appearance and behaviors are similar to those of the bowhead. Right whales have been studied extensively by Payne and his co-workers off southern Argentina (for example: Payne and Payne 1971; Payne 1972, 1974, 1976; Payne et al. 1981), and there have been additional studies by other workers (Cummings et al. 1972; Saayman and Tayler 1973; Watkins and Schevill 1976, 1979). We drew on this knowledge of right whales and compared them to bowheads. This comparative approach will become more fruitful as southern right whale data are analyzed in greater detail, and as bowhead whale studies continue. Much of the field work, analysis and interpretation for the present study were carried out by researchers intimately familiar with right whale behavior.

Approach

Our approach to the normal behavior task (and other tasks), and also the rationale for choice of the eastern Beaufort Sea as the study area, is outlined in the previous section on 'Project Rationale, Design and Summary' (Richardson and Fraker 1982). The following is a brief summary.

Responsibility for the normal behavior work was assigned on a subcontract basis to the New York Zoological Society (NYZS; task supervisor: Dr. R. Payne). Responsibility for other tasks and for logistics remained with LGL Ecological Research Associates, Inc. (the prime contractor) with assistance from Polar Research Laboratory, Inc. (PRL; subcontractor for underwater acoustics). Field work on all tasks was conducted in a coordinated way by LGL, NYZS and PRL.

The date of contract award was 30 June 1980. Fieldwork began in early August 1980 and late July 1981, and continued to mid September of both years. Fieldwork was based at Tuktoyaktuk, Northwest Territories (Fig. 1), a coastal settlement with facilities for personnel, aircraft and boats.

Observations of normal behavior were conducted by aircraft-, boat- and shore-based observers. Aircraft-based observers had the advantage of high mobility and a good vantage point and consequently collected the majority of the data. Sonobuoys were dropped from the aircraft to allow us to hear and record bowhead sounds; boat- and shore-based observers had hydrophones for this purpose. Sonobuoys also allowed us to determine when industrial noises were present in the water; observations of bowheads under such conditions may not represent undisturbed behavior, and have been excluded from the 'Normal Behavior' section of this report.

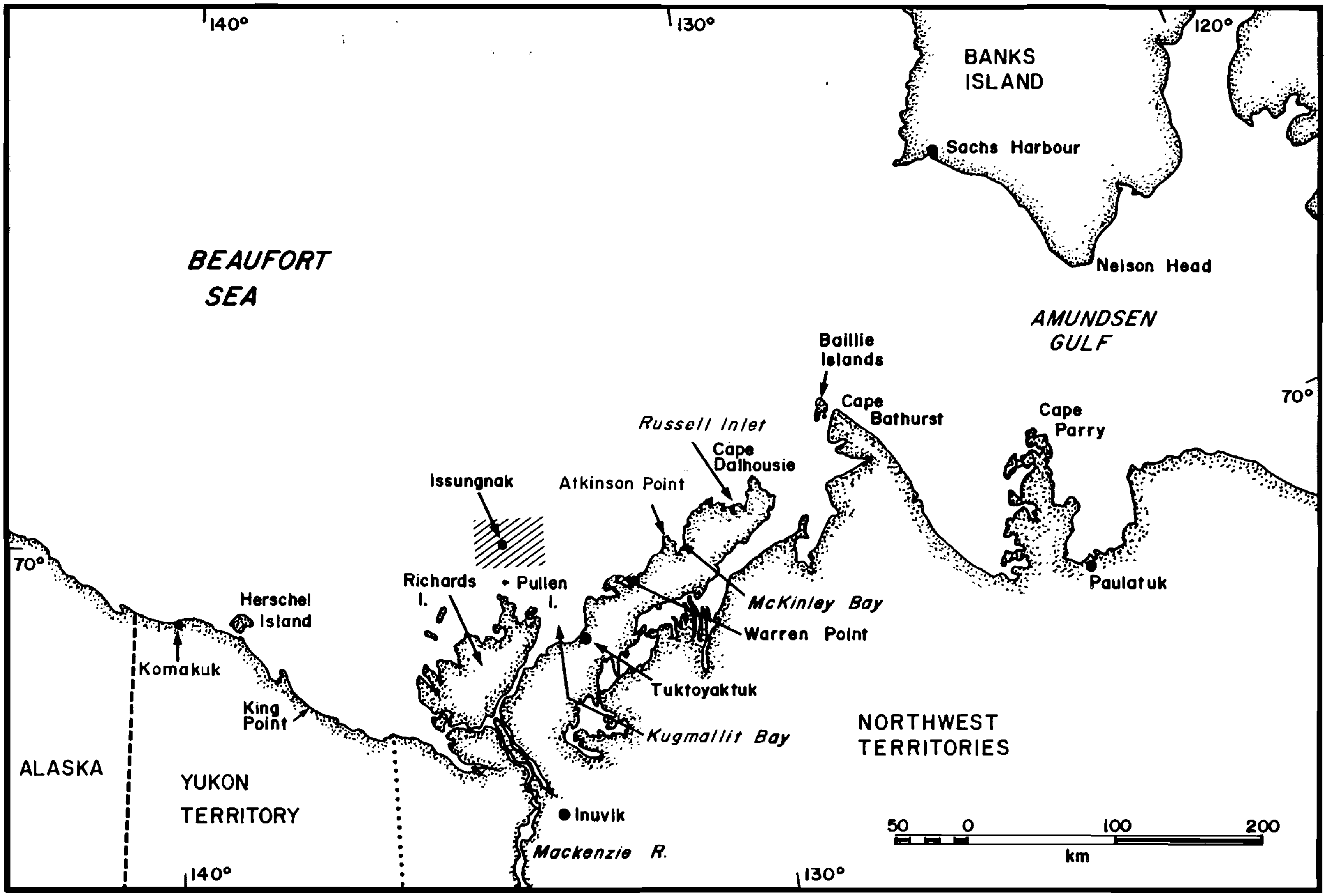

FIGURE 1. The eastern Beaufort Sea region, showing locations mentioned in text. The shaded area around Issungnak was systematically surveyed (50% coverage) four times during August 1980.

METHODS AND DATA BASE

Aerial Observations

We made aerial observations from a Britten-Norman Islander aircraft based at Tuktoyaktuk. The Islander has two piston engines, high wing configuration, low stall speed, radar altimeter and forward-looking radar. The plane was also equipped with an OnTrac VLF/Omega navigational system, which continuously computed the position of the aircraft, usually within 1.8 km of the real position. Positions and flight tracks were recorded from the VLF/Omega system by an onboard computer (HP 9835A) in 1980 and manually in 1981. Sonobuoys (AN/SSQ-41B or AN/SSQ-57A) could be deployed and monitored from the aircraft (details in 'Characteristics of Waterborne Industrial Noise' section, Greene 1982). A handheld color video camera (JVC-CV-0001) connected to a portable videocassette recorder (Sony SLO-340) was used through the side windows to record oblique views of bowheads.

On board were three or four observers and a pilot. In 1980, the observers included two biologists reading behavioral observations into cassette recorders and one operator of the electronic equipment. The biologists were seated in the right front (co-pilot's) seat and in rear seats. While circling over whales, the rear observer was usually also on the right side. In 1981, biologists seated in the co-pilot's seat and in the seat directly behind it described behavioral observations, which were usually recorded onto audiotape, and also were immediately transcribed onto data sheets by a biologist sitting in the left rear. This arrangement worked well, for it allowed feedback from the person filling out data forms to the observers if descriptions were unclear or incomplete. The person taking notes was also responsible for readying and launching sonobuoys and dye markers, and for monitoring sound recording equipment. A fourth researcher in the rear right seat was mainly responsible for videotaping behavioral sequences. The biologists were in constant communication via intercom to avoid duplication of their observations, and in 1981 the intercom audio was recorded onto the voice channel of the video recorder whenever bowhead behavior was videotaped.

In 1980, we made 16 flights between 3 and 31 August and made behavioral observations during 14 of the flights. Total flight duration was 101 hours, and we were within sight of bowhead whales for 30.4 h. In 1981, we made 28 flights between 31 July and 8 September. Total flight duration was 116.8 h, and we were within sight of bowhead whales for 30.8 h. Behavioral observations were made during only 18 of the 28 flights in 1981, because whales were more difficult to locate than in 1980. In 1980, our flights were usually within a radius of 130 km of Tuktoyaktuk. In 1981 bowheads were much less numerous near Tuktoyaktuk, and we often flew 200 km or more to the west, north or northeast. We usually did not fly when wind speed exceeded 25 km/h or when the waves exceeded sea state 3; whales are difficult to detect and behavior is not reliably observable in more severe conditions. While searching for whales, we usually flew at 457 to 610 m (1500 to 2000 ft) above sea level (ASL), and at 185 km/h. While circling over whales, we usually reduced speed to 148 km/h. Bowheads rarely appeared to be disturbed by the aircraft when it remained at or above 457 m (see 'Disturbance' section, Fraker et al. 1982).

Our usual strategy was to search until we encountered bowheads and then to circle over them as long as possible while making observations. Once contact was lost, we searched for another group. We created a fixed reference point about which to circle when bowheads were below the surface by deploying a dye marker (1-2 teaspoons of fluoroscein dye in about 2 liters of water in a plastic bag 1-2 mil thick which burst on impact with the water).

On four days (9, 11, 12 and 22 August 1980) we conducted a systematic grid survey of a 33.3 by 51.5 km area centered on Issungnak, an artificial island located in about 19 m of water north of the Mackenzie Delta (Fig. 1). A dredge was being used to build up the island during this period. During these four surveys we did not circle bowheads to observe their behavior over prolonged periods, but some behavioral information was obtained. These four flights are included in the 101 h total flight duration for 1980, but (with one exception noted below) not in the 30.4 h total for 'time within sight of bowheads'. Results of these surveys are discussed in the 'Disturbance' section. Similarly, on 13 August 1981 we conducted a grid survey encompassing an area 55.5 by 85.1 km around Issungnak. This survey is included in the 1981 total flight duration, but not in the 30.8 h total time within sight of bowheads. The purpose of the 1980 flights was to study bowhead distribution around the dredging operation at Issungnak; the 1981 flight was to locate whales for experimental study and to document their distribution in an area of industrial activity.

We encountered bowhead whales during every day we flew in 1980, and during the majority of the days in 1981. Numbers usually were sufficiently large for us to make an assessment of their basic behavior patterns. Although there were many situations and observable behaviors, we usually were able to obtain consistent records of 15 variables and types of behavior:

1. Location of sighting (and therefore water depth);
2. Time of day;
3. Individually distinguishing features (if any) on whales;
4. Number of individuals visible in area; number of calves;
5. Headings of each whale in degrees true;
6. Distances between individuals (estimated in whale lengths);
7. Length of time at surface and sometimes length of dive;
8. Timing and number of respirations, or blows;
9. Mouth open or closed;
10. Underwater blow (releasing large clouds of bubbles underwater);
11. Defecation;
12. Coming to the surface with mud streaming from the mouth;
13. Socializing and possible mating;
14. Aerial activity: breaches, tail slaps, flipper slaps, lunges, rolls;
15. Type of dive: flukes out, peduncle arch, pre-dive flex.

Descriptions of the various behaviors mentioned above appear later in this report.

The 16 flights of 1980 are summarized in Table 1, and the 18 flights of 1981 (considering only those with behavioral observations) are summarized in Table 2. The resulting behavioral observations were distributed by hour of

Table 1. A summary of aerial observations of bowhead behavior, 1980

Date (1980)	Time over Bowheads			Distance from Shore (km) & Location	Depth of Water* (m)	Estimated Number of Whales	Est. area under obs.** (km^2)	General Behavior	Comments
	Start (MDT)	Stop (MDT)	Total hours						
Aug 3	1612	1815	2.0	80 km north of Tuktoyaktuk & 5-18 km east of Issungnak	18-20 m	10-15	100	Long dive times and much defecation, 2 to 5 whales dive in synchrony	Whales are in the muddier water about 2-3 km from a mud to clear water interface, recognizable whale with harpoon line on back
Aug 4	1910 1943	1931 2036	1.2	80 km north of Tuktoyaktuk & 5-18 km east of Issungnak	18-20 m	10-15	100	Rapid dives upon airplane approach, cannot discern undisturbed behavior	Low cloud cover, airplane altitude of 200-250 m
Aug 6 Flt. #1	0939 1127	1112 1155	2.0	90 km north of Tuktoyaktuk & 15-20 km NE of Issungnak	30-38 m	about 50	100	Whales often within several meters of each other, much pushing and other interactions	
Aug 6 Flt. #2	2017	2226	2.2	90 km north of Tuktoyaktuk and 15-20 km NE of Issungnak	30-38 m	about 50	100	As above - also a lone whale breaches, flipper and tail slaps for 40 minutes	
Aug 7	1408	1609	2.0	85 km north of Tuktoyaktuk & 15 km east of Issungnak	31-36 m	20-30	100	Whales close together as on 6 August	2 recognizable adult whales; one has a white tail; the other has a white triangle on the peduncle (and is with light calf 1/3 size of adult)
Aug 12	1632	1652	0.3	90 km northwest of Tuktoyaktuk & 22 km west of Issungnak	24-29 m	about 20	80	mud streams out of mouths as whales surface	This observation was made during systematic surveys around Issungnak

Continued...

Table 1. Continued

	Time over Bowheads								
Date (1980)	Start (MDT)	Stop (MDT)	Total hours	Distance from Shore (km) & Location	Depth of Water* (m)	Estimated Number of Whales	Est. area under obs.** (km^2)	General Behavior	Comments
Aug 14	1357	1405	0.2	90 km northwest of Tuktoyaktuk & 20 km west of Issungnak	about 26 m	only 2 seen	-	Two whales dive as airplane approaches, cannot discern undisturbed behavior	Low cloud cover, airplane altitude of 200-250 m
Aug 19	1919 2243	2036 2330	2.1	56 km northwest of Tuktoyaktuk & 18 km east of Pullen Island	10-12 m	20-30	25	Whales in very shallow water stir up mud as they move, and exhale often while underwater	A boat moves through these whales and scatters the group (see 'Disturbance' section)
Aug 19	2137	2229	0.9	13 km west of McKinley Bay on the Tuktoyaktuk Penin.	10 m	20-30	50	Whales do not churn up mud, and are blowing underwater very little, some mouths open at surface	
Aug 20 Flt. #1	1040	1140	1.0	25 km northeast of Pullen Island	10 m	20-30	25	Whales in very shallow water stir up mud as they move, and exhale often while underwater	
Aug 20 Flt. #1 Flt. #2	1140 1324 1902	1306 1358 2018	3.3	25 km northwest of Warren Point	12 m	20-30	25	Whales churn up some mud	Recognizable whales seen again—white tail, white triangle on peduncle and (small) calf
Aug 20 Flt. #2	2021	2058	0.6	18 km north of McKinley Bay	18 m	20-30	25	Mouths possibly open	

Continued...

Table 1. Continued.

Date (1980)	Time over Bowheads			Distance from Shore (km) & Location	Depth of Water* (m)	Estimated Number of Whales	Est. area under obs.** (km^2)	General Behavior	Comments
	Start (MDT)	Stop (MDT)	Total hours						
Aug 21	2229	2330	1.0	20 km north of Warren Point	12-13 m	about 7	9	Short periods at surface	
Aug 22	1043	1119	0.6	20 km north of Warren Point	12 m	about 10	9	Whales at surface singly or in small groups, no specific behavior discernible	
Aug 22	1124	1415	2.9	18 km north of McKinley Bay	12-14 m	20-30	50	Whales' mouths open as they move slowly at surface, often 2 or more staggered side by side, one lone whale breaches, flipper and tail slaps	
Aug 23	1027	1203	1.6	about 24 km north of McKinley Bay	18-22 m	20-30	50	Mouths open; slowly moving at surface, dive synchrony by 5-10 whales	
Aug 27	1256 1408	1317 1627	2.6	22-27 km north of McKinley Bay	17-19 m	15-20	50	Whales' mouths not open, milling at surface	Disturbance trials with boat and 4 whales (see 'Disturbance' section)
Aug 29	1212 1241 1436	1222 1420 1438	1.9	30 km west-northwest of Baillie Island	24 m	about 8-10	50	Whales mainly in small groups of two to three, much interacting	Recognizable whales - high white chin and a white peduncle

Continued...

Table 1. Concluded

	Time over Bowheads								
Date (1980)	Start (MDT)	Stop (MDT)	Total hours	Distance from Shore (km) & Location	Depth of Water* (m)	Estimated Number of Whales	Est. area under obs.** (km^2)	General Behavior	Comments
Aug 31	1215 1451 1511	1437 1459 1523	2.7	50 to 65 km north of the Tuktoyaktuk Penin., spread from Warren Point to Cape Dalhousie	23-28 m	more than 20	650	Whales mainly in small groups of two to three, some interacting	Whales spread over large area, far from shore

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* Location was determined from the VLF navigation system on the aircraft, and water depth for the corresponding latitude and longitude was taken from hydrographic charts.

** This is the approximate area over which the aircraft circled and within which the 'Estimated Number of Whales' were found.

Table 2. A summary of aerial observations of bowhead behavior, 1981.

	Time over Bowheads							
Date (1981)	Start (MDT)	Stop (MDT)	Total hours	Distance from Shore (km) and Location	Depth of Water* (m)	Estimated Number of Whales	Est. area under obs.** (km^2)	General Behavior and Comments
5 Aug	1005	1158	1.9	85 km N of Pullen Isl.	68	5	25	Some socializing; defecating; possible subsurface feeding; seismic pinging throughout
6 Aug	2250	2255	0.1	98 km NNW of Pullen Isl.	69	1	25	Subadult, very active at surface
8 Aug	1920	1930	0.2	139 km N of Atkinson Pt. off Tuktoyaktuk Pen.	65	1	25	A recognizable whale; inactive near the surface
	1957	2116	1.3	139 km N of Atkinson Pt. off Tuktoyaktuk Pen.	65	2	25	Inactive near the surface; among loose ice
	2124	2128	0.1	139 km N of Atkinson Pt. off Tuktoyaktuk Pen.	65	1	25	Slowly travelling
10 Aug Flt. #1	1243	1255	0.2	176 km N of Atkinson Pt., Tuktoyaktuk Pen.	690	2	25	Slow or no movement
	1424	1431	0.1	148 km N of Russell Inlet, Tuktoyaktuk Pen.	152	5-10	25	Slow or no movement. Apparent precopulatory interaction; two animals
	1448	1518	0.5	148 km N of Russell Inlet, Tuktoyaktuk Pen.	152	10-15	25	Slow or no movement
10 Aug Flt. #2	2027	2041	0.2	70 km NW of Pullen Isl.	38	15-20	25	some socializing

Continued...

Table 2. Continued

Date (1981)	Time over Bowheads Start (MDT)	 Stop (MDT)	 Total hours	Distance from Shore (km) and Location	Depth of Water* (m)	Estimated Number of Whales	Est. area under obs.** (km^2)	General Behavior and Comments
	2107	2241	1.6	70 km NW of Pullen Isl.	38	20-30	25	Much socializing
13 Aug	1155	1327	1.5	70 km NW of Pullen Isl.	43	10-15	50	
18 Aug Flt. #1	1029	1304	2.6	44 km NW of Pullen Isl.	26-38	10-15	50	
18 Aug Flt. #2	1827	1948	1.5	35 km NNW of Pullen Isl.	23-28	20-30	50	Subsurface skim feeding
	2010	2119	1.4	35 km NNW of Pullen Isl.	23-28	20-30	50	Subsurface skim feeding
19 Aug	1247	1528	2.7	33 km NNW of Pullen Isl.	25	10-15	25	
23 Aug Flt. #1	1115	1136	0.4	44 km NW of Pullen Isl.	34-36	5-6	25	
	1148	1158	0.2	48 km NW of Pullen Isl.	45	5-6	25	
23 Aug Flt. #2	1815	1917	1.0	35 km NW of Pullen Isl.	28-31	30-40	300	Some echelon feeding; some socializing
	1935	1948	0.2	35 km NW of Pullen Isl.	23	30-40	300	Socializing mainly
	2017	2044	0.5	35 km NW of Pullen Isl.	23	30-40	300	Socializing mainly

Continued...

Table 2. Concluded

	Time over Bowheads							
Date (1981)	Start (MDT)	Stop (MDT)	Total hours	Distance from Shore (km) and Location	Depth of Water* (m)	Estimated Number of Whales	Est. area under obs.** (km^2)	General Behavior and Comments
24 Aug	1405	1739	3.6	33-46 km NW of Pullen Isl.	28-39	30-40	300	A little echelon feeding; possible water column feeding; calves stay at surface while adults dive
25 Aug	1121	1418	3.0	19-22 km NW of Pullen	10-13	15-20	300	Mud streaming out of whale mouths; log playing; apparent precopulatory behavior
3 Sept Flt. #1	1118	1147	0.5	1-10 km from shore of Herschel Isl.	?	6-10	25	
	1157	1206	0.2	1-10 km from shore of Herschel Isl.	?	6-10	25	
	1215	1314	1.0	1-10 km from shore of Herschel Isl.	?	6-10	25	
3 Sept Flt. #2	1824	1831	0.1	1-10 km from shore of Herschel Isl.	?	6-10?	25	
6 Sept	1753	1940	2.1	41 km N of Komakuk Beach, Y.T.	53	6-10?	300?	Mouth open by one whale one time
7 Sept	1148	1302	1.2	7-9 km W of Herschel Isl.	22-30	6-10?	300?	
8 Sept	2112	2216	1.1	11-13 km W of Herschel Isl.	26-30	10-15?	300?	

*, ** Defined as in Table 1.

day as presented in Figure 2. These observation times are divided into periods when there was no known potential man-made disturbance in the observation areas, and periods when there was potential disturbance. In this section of the report, we will describe only the behavior observed with no known potential disturbance. Data collected during the periods of potential disturbance are described separately in the 'Disturbance' section (Fraker et al. 1982). The numbers of hours of behavioral observation over different water depths are shown in Figure 3; observations in 1981 were usually in deeper water than in 1980.

Shore-Based Observations

Shore-based observations were obtained in both 1980 and 1981 from the southeast bluffs of Herschel Island, Yukon Territory (69°35'N; 138°51'W), about 210 km west of Tuktoyaktuk. To obtain horizontal and vertical bearings for each whale sighting, a surveyor's theodolite was used from a high point (50 m ASL in 1980 and 90 m ASL in 1981) on the coast. In 1980 we used a Wild theodolite, Model T1, with 6 sec accuracy and 30-power optics. In 1981 we used a Nikon theodolite, Model NT-2A, with 20 sec accuracy and 30-power optics. The bearings could later be translated to x and y coordinates on a map of the area. Behavioral observations by the theodolite operator were also recorded. This technique, developed by R. Payne, is described by Würsig (1978a). The station was in use from 19 August to 11 September 1980, and 23 August to 13 September 1981.

Observers on the bluff took turns at the theodolite. Figure 4 shows the watching effort from the theodolite site by hour of day for each year. Usually one observer looked through a telescope or binoculars and reported blows to the theodolite operator, who then located the whale making the blow and determined its horizontal and vertical bearings. Locations of most whales within a 10 km radius of the theodolite station during fair weather and daylight hours were documented. Unfortunately, whales rarely approached Herschel Island closer than 5 km during the 1980 field season, so details of behavior were difficult to discern. In 1981, fewer whales were seen, but they were closer to shore, allowing more detailed behavioral observations. In both years the whales seen often appeared to be lingering in the area rather than migrating rapidly through.

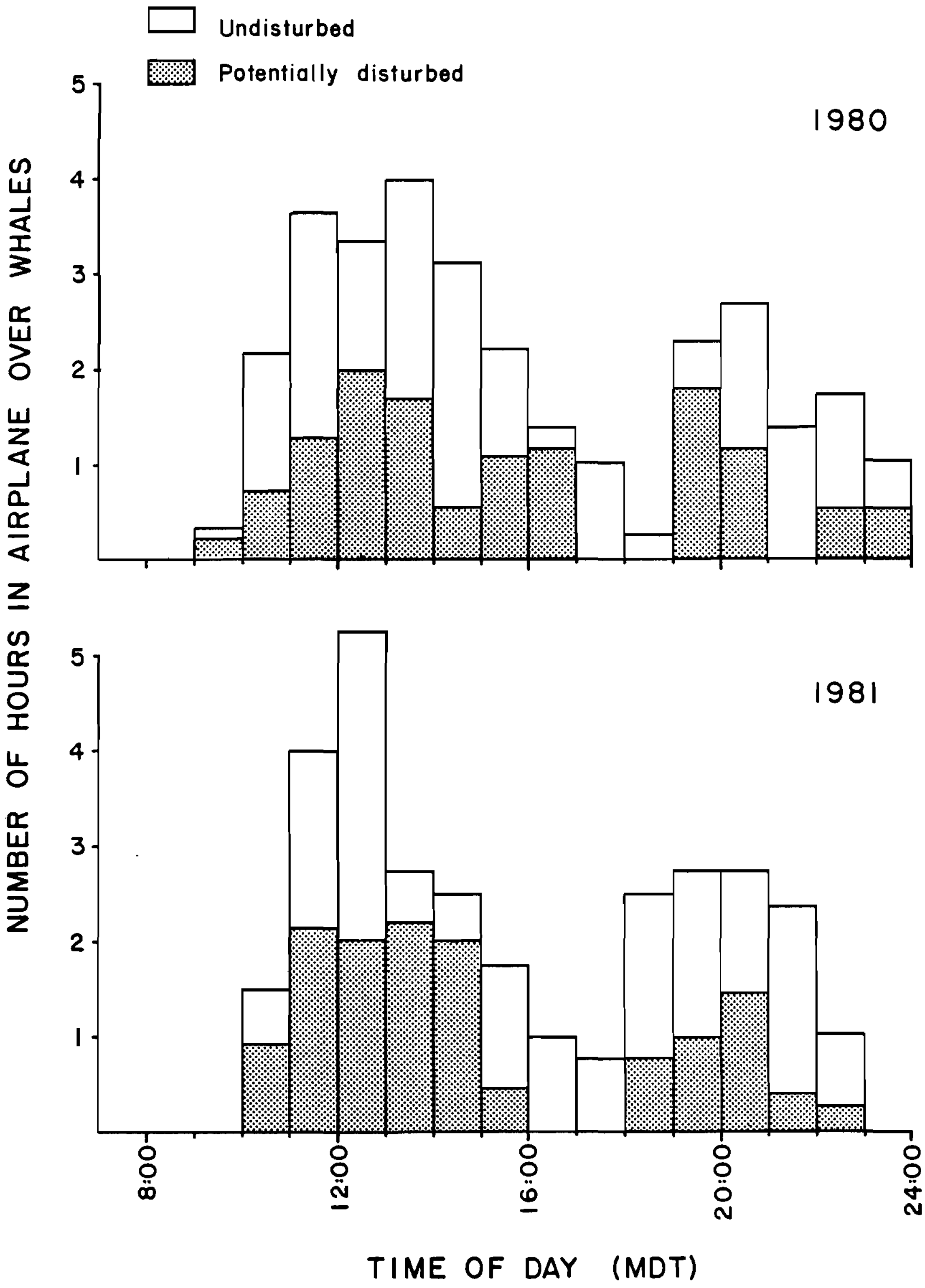


FIGURE 2. Hourly distribution of behavioral observation time from the air, 3-31 August 1980 and 5 August-8 September 1981. Time spent over presumably undisturbed whales is distinguished from time spent over potentially disturbed whales.

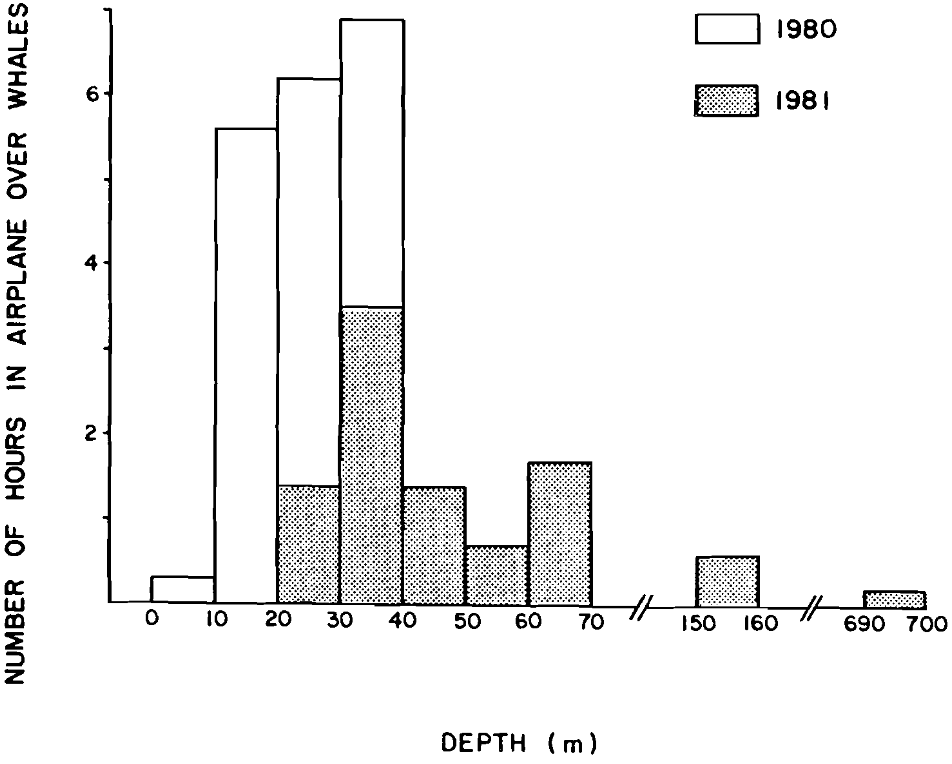


FIGURE 3. Distribution of behavioral observation time from the air by depth of water for 1980 and 1981. Only the presumably undisturbed periods are included.

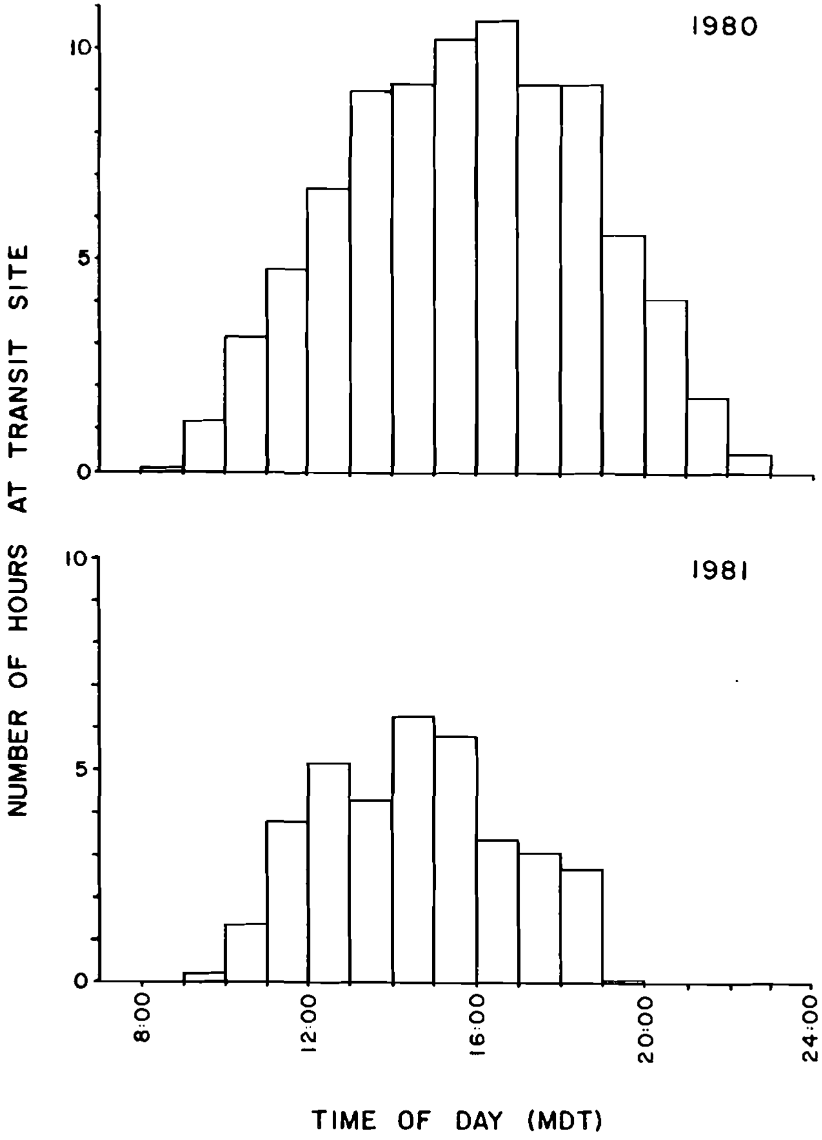


FIGURE 4. Hourly distribution of time spent watching from the Herschel Island transit site, 19 August-11 September 1980 and 23 August-13 September 1981.

A second shore camp--at King Point along the mainland coast of the Yukon (69°04'N, 138°00'W)--was manned from 16 August to 13 September 1980, and from 19 August to 3 September 1981. In some previous years bowheads appeared close to shore at this location in late summer (Fraker and Bockstoce 1980). However, in 1980 only one bowhead was sighted from King Point; this was on 18 August. In 1981, blows, probably from bowheads, were heard offshore in fog on 18 and 19 August. These probably represented one whale on each day. The 18 August blows indicated that the whale making them was travelling westward. On 3 September 1981, a bowhead whale that appeared smaller than a full-grown adult was observed from King Point travelling toward the northwest about 1 km from shore.

Boat-Based Observations

Three boats in the 12-16 m class were used for various purposes in this project. During 1980, some behavioral observations were obtained from the 'Ungaluk' and the 'Imperial Adgo'. The 'Ungaluk' is a 14 m sailing vessel with auxiliary diesel; it was used off the Mackenzie Delta from 7 to 14 August 1980. The 'Imperial Adgo', a 16 m vessel, was used to obtain behavioral data from 23 to 27 August 1980. It is fast (up to 40 km/h) and thus very efficient in approaching whales and obtaining information, especially on whale orientations relative to the boat. During 1981, the 12 m diesel vessel 'Sequel' was used to observe whales from 31 July to 6 September. Because observations from the boats pertain mostly to experimental disturbance trials, they are detailed in the 'Disturbance' section of this report.

RESULTS AND DISCUSSION

Descriptions of Behaviors

The behaviors of bowheads that we saw can be described as follows:

Blow

A blow is an exhalation of air by a whale; it usually occurs when the whale's nostrils are above the surface, but can occur with nostrils below the water surface as well. Blows are of variable detectability, probably owing to differences in the force of the exhalation and in the amount of water accumulated near the blowholes. It is almost certain that not all blows are detectable. Blows by calves sometimes are especially difficult to see. The blow interval is the time between visible blows while whales are at the surface. We had no means of estimating the volume of air exhaled, but differences in height of the spout indicate that considerable variation in volume or force occurs.

Surface Blow

The surface blow is usually forceful and short, lasting about one second. It looks very much like that of the southern right whale, although we never saw bowheads produce the extended exhalations lasting 2-3 s which right whales sometimes give on their breeding grounds. The first blow after a dive often appears more forceful than others, possibly because more water may be collected over the blowhole at that time. Blows in calm water and by animals lying quietly at the surface can be difficult to see.

Defecation

Defecation usually consists of a cloud (2-3 m in diameter) of red-orange feces near the surface. Whales almost invariably moved forward or dove upon defecating, and well over 50% of the bowheads observed defecating in 1980 did so while the tail was arched up high out of water just before the dive. The anus was thus very close to or even at the surface, and no part of the body appeared to touch the feces cloud. This cloud was visible at the surface for up to 10 min. When whales moved forward while defecating, the feces were more dispersed, and disappeared within 1-2 min. Brown (1868) noted that the feces of eastern arctic bowheads were also red, and Renaud and Davis (1981) observed red clouds of feces off the Tuktoyaktuk Peninsula in 1980. Although 23 defecations were observed during 30.4 h over whales in 1980, only 11 were seen during 30.8 h over whales in 1981. The difference is statistically significant (chi-square = 4.39; df = 1; $0.025<p<0.05$), and may be related to year-to-year differences in feeding patterns.

Tail Beats

A whale moving rapidly at or slightly below the surface often leaves a trail of circular surface disturbances representing the locations where the flukes change direction from their upward to their downward swing. These circles, termed fluke tracks and caused by upward moving water, are seen in all species of whales when they are swimming close to the surface and can be used to count the number of strokes the whale uses to propel itself a given distance. In bowheads, each tail beat near the surface propelled the animal forward by approximately one whale length, or about 15 m.

Pre-dive Flex

The pre-dive flex is a distinctive concave bending of the back seen just before many bowhead dives. The whale flexes its back by about 0.5 to 1 m, so only the snout and tail are visible at the surface. This action usually creates considerable whitewater along the back, especially at the tail. The whale then straightens its back and lies momentarily still at the surface before commencing its dive. This pre-dive flex occurs about 3-7 s before the actual dive.

The pre-dive flex was seen more often during 1980 than during 1981. Although it occurred previous to dives well over 50% of the time in 1980, it occurred only 8% of the time (before 29 of 352 dives) in 1981. One major difference in observation circumstances during the two years was water depth (Fig. 3); this may have influenced the frequency of pre-dive flexes. However, analysis of 1981 data shows no relationship between frequency of this behavior within that year and either depth of water or type of behavior (socializing, feeding, or aerial activity). We have no explanation for why a behavior that was so consistently present during one year was seen much less often (by the same observers) during the subsequent year.

Dive

During the dive, which can often be predicted by the pre-dive flex, the whale makes its back convex and forces the head underwater; the whale pitches forward while the flukes either lift out of the water or stay just below the surface. As in other species, the angle at which the whale submerges correlates with whether or not the tail appears above the surface; when it does, the whale dives steeply. Only rarely did a bowhead just sink below the surface without visibly arching its back. Our observations of behavior preceding and during dives are similar to the description given by Scoresby (1820) for eastern arctic bowheads:

> "When it retires from the surface, it first lifts its head, then plunging it under water, elevates its back like the segment of a sphere, deliberately rounds it away' towards the extremity, throws its tail out of the water, and then disappears."

The length of a dive was measured from the time a whale left the surface and disappeared from view underwater to the time it re-appeared at the surface. Dives could be measured only for whales that were in some way individually recognizable. Brief submergences when the whale remained visible from the air were not scored as dives or as interruptions of surfacings. Thus, dives were defined as periods when the whales were invisible below the water. These periods ranged in duration from a few seconds to many minutes (details in a later section). Sometimes whales were just below the surface and clearly visible from the aircraft. Such periods were not considered to be dives except on the few occasions when whales were visible but underwater for >1 min.

Aerial Activity

Bowhead whales at times leaped or breached from the water, so that one-half or slightly more than one-half of the body was clear of the water. The whale comes out of the water head first and at a small angle from the vertical, usually with the ventrum down. It then twists slightly and falls back onto the water on its side or back, creating a large splash. A series of breaches by one whale on 6 August 1980 were spaced an average of 45.5 s apart (n = 12, s.d. = 11.89).

Whales also 'forward lunged' by coming out of the water at an angle and not twisting the body, but instead re-entering belly first. During forward lunges, the whale propels itself a few metres forward at the surface. In contrast, the breach does not have any appreciable forward component.

Tail slapping was another form of aerial activity. During tail slapping, the whale's head and most of its torso are below water, and the tail is rapidly and usually repeatedly lifted high into the air (often as much as 1/4 of the body length) and then slammed forcefully onto the surface of the water. Usually the tail was parallel to the surface when it hit the water, but at times the tailstock was twisted a bit and the tail hit obliquely, re-entering the water with one fluke tip first and ending in a welter of foam. The whale that we observed breaching repeatedly on 6 August 1980 had 3 bouts of tail slapping at a rate of one tail slap every 7.5 s (n = 30, s.d. = 6.15) within the bouts. Although we saw some tail slapping without other aerial activity, forceful tail slapping was usually interspersed with breaches.

We also saw pectoral flipper slapping, wherein the whale would lie on its side and forcefully slap the water surface, usually with the ventral surface of a flipper. Flipper slapping occurred once every 4.2 s (n = 5, s.d. = 1.48) in a short sequence observed on 6 August 1980; this was by the same active whale noted above.

All three aerial activities involved violent disruptions of the surface and probably produced sounds underwater, as they are known to do in southern right whales (Clark 1982b). Breaches at times ended in a tail slap; after the whale fell back into the water and before it submerged completely, the tail was forcefully slapped onto the surface.

In 1980, six bouts of aerial activity were seen from the air. These were all on different days, and presumably were by different whales. In 1981, we observed 14 such bouts, but the difference between years is not significant (chi-square = 3.20, df = 1; $0.05<p<0.10$). In 1980 most of the aerial activity consisted only of the forceful breaches, tail slaps, and pectoral flipper slaps discussed above, whereas during 1981 approximately one-third of the aerial activity occurred while one or two animals at the surface actively turned on their longitudinal axes. This behavior, termed rolling, was often associated with pectoral flipper slapping or tail slapping, but rolling itself presumably does not create much underwater noise. Rolling was done while one or more other whales were nearby, and it appeared to have a social function (see 'Possible Mating' below). Rugh and

Cubbage (1980) witnessed breaching by 23% of all bowheads (n = 280) that they saw at Cape Lisburne, AK, in spring. This suggests that breaching may be more frequent during spring migration than in summer.

Head Slamming

This behavior was only seen once during approximately 61 h of aerial observations, but it was very noticeable. The whale, while pointed away from the aircraft, alternately flexed and relaxed its back while the head pounded the water surface three times. We have seen head slamming in aggressive situations in right whales (Payne 1976), but we have no other reason to suspect that this incident was also an aggressive action. The behavior lasted for about 5 s.

Pushing

When bowhead whales touched, they often appeared to push each other, although it was rarely possible from the aircraft to be sure that one of them actually propelled the other through the water. Pushing or touching is usually done with the head and with the whales oriented head to head or head to tail. Sometimes other parts of the body are involved. We witnessed whales of adult size diving under the bellies of other whales and apparently nudging or pushing the other whales near their genital areas. At other times, whales dove under each other at very close range without any indication that they were touching.

Possible Chases

Apparent chase sequences involved two or three whales in a line, usually only 2 body lengths apart. They stayed at the surface while moving rapidly, and often dove or surfaced almost synchronously, with the lead animal doing so slightly before the next one and so on. Apparent chases also often involved the first animals abruptly turning left or right, and the second (and third) following. During 'chases', movement was appreciably faster than it was at all other times when we saw whales at the surface.

Aggressive Tail Thrashing

Perhaps the clearest example of intraspecific aggression that we observed occurred on 24 August 1981, approximately 40 km northwest of Pullen Island. An adult with a calf was approached rapidly and closely by two other adult whales. As they approached, the presumed female turned away from the two other adults and thrashed its tail violently within about 5 m of the head of one of the adults. Both of the approaching adult whales turned and moved away. The calf was not at the surface during this brief interaction.

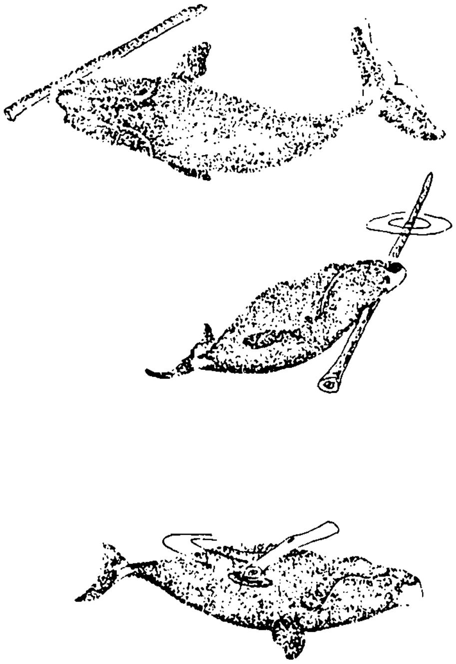
Possible Mating

In 1981 in two different instances we observed social behavior that appeared to be copulation or attempted copulation--two whales rolling ventrum to ventrum at the surface with associated behavior that looked very similar to courtship and mating in southern right whales. In one case, one bowhead appeared to be attempting to avoid the other animal, while in the second case the inclination to copulate appeared to be mutually shared. More detailed descriptions are given in 'Social Behavior', below.

Log Playing

During 1981, we witnessed two incidents of whales touching logs that were floating on the water. On 10 August, a whale briefly nudged the middle of a long (about 20 m) log, propelling it about 5 m forward. The whale then dove under the log and we did not see that whale again. Although the interaction lasted only 5 s, it was apparent that the whale did not simply bump into the log accidentally; it oriented toward the log and pushed it. A more dramatic incident occurred on 25 August 1981. A small (possibly yearling) whale was first observed just underneath a log approximately 10 m long. The whale nudged and pushed the log and lifted it onto its back so one end was perhaps 3-5 m above the surface for 1-2 s. This small whale was then joined by two adults that surfaced close to the log. At least one of the adult whales let the log roll over its back, and on two occasions in the 10 min during which we witnessed the behavior, the whale rolled ventrum up underneath the log and clasped the log with its flippers. During this time, there were some nudges and close associations between the whales not touching the log. The apparent log playing seemed to be associated with a high level of social activity.

Our observations do not represent isolated instances. Other personnel from LGL Ltd., while conducting large-scale aerial surveys, saw bowheads apparently playing with logs on at least two other occasions within the same general vicinity (18-20 km northwest of Pullen Island) and within the same week.



Although playing with logs has, to our knowledge, not been documented previously for bowhead whales, association with objects other than conspecifics has been described for many marine mammals. Right whales play with objects tethered in the sea and with kelp (Payne 1972, 1976; Reeves 1975), and some gray whales associate with boats for long periods of time (Swartz 1977). There is a report of a humpback whale breaking up log booms in Puget Sound, but what activity by the humpback resulted in the break up is not known (Couch 1930). There is also a report of a sperm whale apparently biting a log while several other sperm whales appeared to chase the first whale (Nishiwaki 1962).

Synchrony

At times whales surfaced, dove, and even blew in synchrony or near-synchrony. Sometimes entire groups of about one dozen whales in an area with a diameter of several kilometres appeared to be almost all at the surface or below the surface at any given time. Whales that surfaced together and were within about one or two whale lengths of each other sometimes blew synchronously as well.

Orientations

Within groups of whales, there often appeared to be a predominant orientation. Whether this was a social synchrony or whether the whales were independently reacting to environmental stimuli (such as currents or wave patterns) is not known. Most bowheads moving through an area while migrating are headed in the same direction (Braham et al. 1980b; Davis and Koski 1980; Fraker and Bockstoce 1980; Renaud and Davis 1981), but whales observed during most of the present study did not appear to be migrating (see below). Patterns of seasonal movement in our study area in 1980 are discussed in Renaud and Davis (1981); movements in 1981 are presently being analyzed as part of a separate project (LGL Ltd., in prep.).

Adult-calf Pairs

Calves seen during the present study were lighter in color than adults and about one-half the length of the associated adult. Six calves measured from videotape sequences were a mean of 0.57 ± s.d. 0.052 adult lengths. We assume that the adult companion of each calf was its mother. Adults and their calves were usually within one adult-length of each other. An analysis of videotape sequences gives the mean distance between adult and calf as 0.61 adult whale lengths (s.d. = 0.564, n = 8, range = 0.1 to 1.5), or about 9 m. The calves spent most of the time lying beside the adult and facing in the same direction as the adult. At times the calf strayed up to two whale lengths from the adult and then oriented toward the adult. While the adult lay at the surface, the calf often submerged near the belly of the adult, with its tail close to the adult's tail. This position may be indicative of nursing. The calf then often swam under the adult, surfaced on the other side, respired several times, and submerged again on the new side. When this happened, the calf alternated sides with each surfacing. The calf also appeared at times to rest, lying quietly on the back and tail of the adult.

On 24 August 1981, we witnessed three calves separated from each other and from the closest adults by 100 m to more than 300 m. It was therefore often not possible to assign calves to particular presumed cows. The nearest adults spent much time submerged but the calves remained stationary at the surface. At one point we videotaped an adult that surfaced 4.9 adult lengths from a calf which was lying stationary at the surface. During another videotape sequence, an adult-calf pair, 0.2 lengths apart, was separated from a lone calf by 7.6 adult lengths. We obtained the impression that the adults were feeding in the water-column and that the calves were 'waiting for them' at the surface. There have been other observations of calves at the surface in the absence of any detectable adult (Renaud and Davis 1981), so synchronous diving by the cow and calf is not an invariable rule. Furthermore, we observed a calf off Herschel Island that was aerially active independently of its presumed mother for almost 30 min and became separated from her by about 1 km during that time (see 'Shore Observations', below).

The aerial observations of behavior were not suitable for obtaining an unbiased estimate of the proportion of the population composed of calves, but observations during systematic aerial surveys were more suitable for this purpose. Two sets of systematic surveys were done in the eastern Beaufort area during 1980. Of the 126 bowheads seen on-transect (within 0.8 km of the survey route) during our four systematic surveys around Issungnak, five (4.0%) were calves. Of 209 bowheads detected on-transect during three systematic surveys off the Tuktoyaktuk Peninsula, six (2.9%) were calves (Renaud and Davis 1981). The latter surveys were conducted on 6-7 and 21-24 August and on 3-4 September 1980. The single survey on 21-24 August 1980 found 6 calves in 158 animals, or 3.8% calves. If the results of the two studies are pooled, 11 of 335 bowheads (3.3%) were calves. Each of the above studies contained significant chances for double- or multiple-counting of individuals, so the sample size of independent animals is probably smaller than 11 of 335. Cubbage and Rugh (1981) and Davis et al. (1982) provide additional data concerning calf : adult ratios in this area.

Our results are similar to percentages recorded off Point Barrow, AK, in spring (1.6-3.5%, Braham et al. 1980b; Johnson et al. 1981). Although results from both areas have limitations, there is to date no evidence from calf-count data that significant numbers of calves are born after bowheads pass Point Barrow. Similarly, Durham (1979, 1980) has reported that only very small embryos, not near-term fetuses, have been recovered from female bowheads taken during the spring hunt; however, the sample size is small.

These results, and similar low percentages for the bowheads of the Davis Strait/Baffin Bay population (Davis and Koski 1980), indicate that the present-day productivity of the bowhead populations in the North American arctic is low compared to the productivity of baleen whale populations in general (4-8.5%, Ohsumi 1979).

Feeding Behavior

Feeding appeared to occupy much of the time of the bowheads that we observed, and we identified four types of behavior that were definitely or possibly associated with feeding. The evidence for classifying various behavior patterns as feeding was largely circumstantial. We could not kill an animal and examine its stomach contents to determine whether it had been feeding recently. We had to rely on clues, such as observations of swimming with open mouth and the presence of feces in the water, to indicate that feeding had taken place. The possible types of feeding behavior that we identified are

1. Water-column feeding;
2. Near-bottom feeding;
3. Skim feeding;
4. Mud tracking.

Of these categories, the first three rather clearly represent feeding, whereas the function of the last is uncertain. Another behavior, underwater blowing, showed some association with feeding but the connection is uncertain. Hence we treat it in a separate section.

In 1980, we found that certain feeding behaviors occurred in particular areas: only water-column feeding was seen near the Issungnak artificial island site, whereas only skim-feeding was seen off the Tuktoyaktuk Peninsula near McKinley Bay. In 1981, feeding was seen less often than during the previous year.

Water-column Feeding

Water-column feeding could not be observed directly, and it was not always possible to determine whether the whales under observation were feeding below the surface. Whales were scored as feeding in the water column when they dove for long periods and when, between long dives, there was much defecation and only slow forward motion. Often conditions were good enough for us to see that their mouths were open while engaged in this behavior. Defecation alone is simply an indication of prior feeding. However, particular behaviors--such as a series of long dives--usually continued for many hours, so occurrence of defecations between long dives was considered indicative of ongoing feeding in the water column.

The frequency of water-column feeding was not constant. In 1980, we saw bowheads water-column feeding from 3 August, the date of the first flight, until 22 August. Thereafter it appeared that few whales were present in the areas where we had observed this behavior. In 1981, when we saw less defecation, we only scored as water-column feeding some adult whales on 24 August that dove for prolonged periods while calves remained at the surface. Because feeding below the surface cannot be observed directly, it may have occurred during many other dives besides those that we classified as dives with water-column feeding.

Observations on 3 August 1980 typify water-column feeding behavior. On this date, bowheads were north of Kugmallit Bay in an area where the water depth varied from 18 to 38 m. The surface water was turbid, fresh water from the Mackenzie River, but beneath this surface layer there was probably a second layer of clearer, saline Beaufort Sea water (see 'Characteristics of Feeding Areas' section, Griffiths and Buchanan 1982). The whales occurred in groups of 2-10 animals and occasionally as individuals without any physically close associates. The members of groups showed a high degree of synchrony, often surfacing very close together and remaining close at least until they dived again. Not only did the members of a group surface and dive synchronously, but various groups spread over an area several kilometres in diameter tended to all be at the surface or beneath it at the same time.

While the animals were at the surface, they moved slowly forward while taking a series of breaths. As each individual dived, it raised its tail clear of the water and disappeared from view in the turbid water. Thus, these dives must have taken the whales well below the surface. When the whales were at the surface, they often disturbed the turbid surface layer, exposing dark patches of sea water from deeper depths; however, while submerged after a dive that was preceded by raised flukes, they did not affect the thin surface layer, indicating that they were probably feeding in the underlying clearer ocean water. Defecation was frequent, suggesting that feeding may have taken place recently. The feces clouds were red-orange in color.

Bottom Feeding

On 12 August 1980, during a systematic survey of the Issungnak area, we noticed clouds of mud suspended in the water about 25 km west of Issungnak artificial island (Table 1, Fig. 1). We believe that mud was involved, and not clouds of plankton, because the material was of the same color as mud dredged up by oil-related activities. As we circled above this area, whales surfaced streaming large amounts of muddy water from their mouths, indicating that they had been feeding from or near the bottom. (We had observed similar mud clouds in this same area during a systematic survey on 9 August; at that time we could not remain in the area to make observations.) This behavior occurred in approximately 24-29 m of water and seemed to be very localized. We saw no indication of bottom feeding in the same area on 22 August 1980.

On 12 August 1980, we watched with particular care to be sure that the mud cloud we saw was issuing from the whales' mouths and not from mud adhering to their heads. We were convinced that the mud came directly from the mouth. The mouths of these whales were open slightly, allowing water to flow through the baleen. At times the whales appeared to wash their baleen by repeatedly opening and closing their mouths. A tendency toward synchrony of surfacing was apparent with these whales; sometimes no whales could be seen, but at other times there were many whales at the surface, all with muddy water issuing from their mouths.

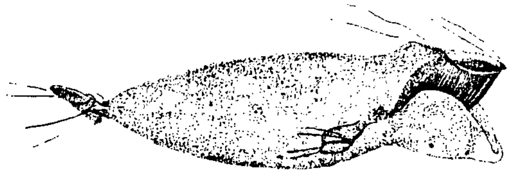
On 25 August 1981, whales again surfaced with mud streaming from their mouths. The location of this bottom feeding was approximately 15 km south of the position where we observed such behavior in 1980; water depth was only 10-13 m.

These are, to our knowledge, the first reported behavioral observations of apparent near-bottom feeding by bowhead whales. However, Lowry and Burns (1980) remarked that "The presence of pebbles and bottom-dwelling species indicates that all the whales taken at Kaktovik had fed at least partially near the sea floor".

Bottom-feeding whales were usually separated from other whales by 10 to 20 body lengths (150 to 300 m) when at the surface. From an altitude of 610 m on 12 August 1980 we could see, within an area of 3 km radius, at least 10 whales that had been bottom feeding. Whether they were feeding on inbenthic or epibenthic invertebrates we do not know. In the eastern Beaufort Sea, the average biomass of inbenthic animals greatly exceeds that of epibenthic animals (see 'Feeding Areas' section, Griffiths and Buchanan 1982). However, the latter may occur in dense swarms in certain places. Such swarms would seem to be, for a balaenid whale, a more suitable type of food than inbenthos, and mud might be taken inadvertently along with the epibenthic animals.

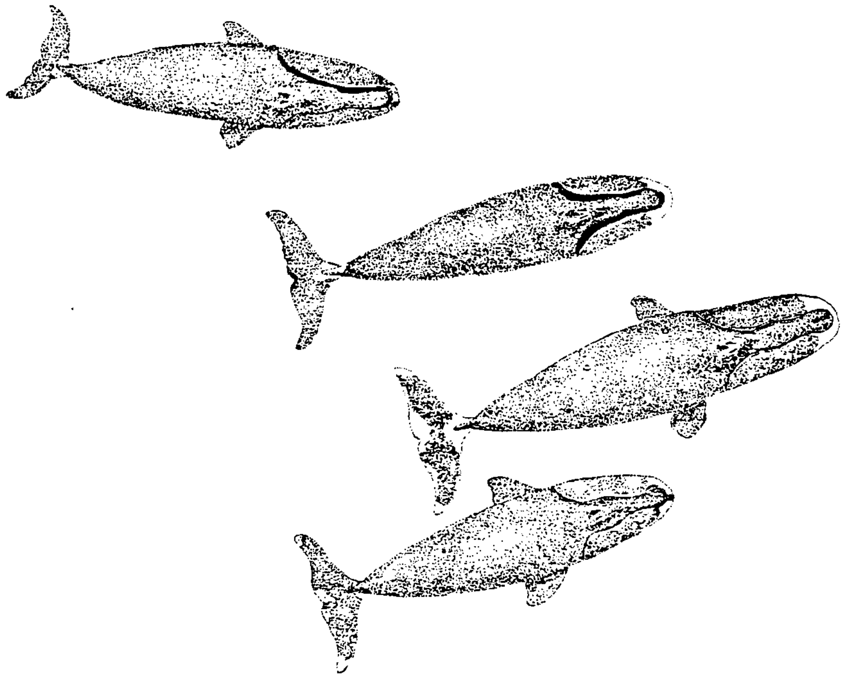
Skim Feeding

The only feeding type that we observed directly was skim feeding. In the third week of August 1980, we observed whales moving slowly and deliberately at the surface with their mouths open wide. The rostrum just broke the surface of the water and was parallel to it. The lower jaw was dropped to varying degrees, as could be seen from the depth of the white chin patch. In 1980, skim feeding was observed along the Tuktoyaktuk Peninsula in water ranging from 12 to 22 m in depth. Whales occasionally skim fed alone, but more often they did so in groups of 2 to 10 or more individuals. During any one observation period, they stayed in the same general area and did not appear to make any net geographic movement. However, we found groups of skim feeding whales in different locations on different days.



During 1981, we witnessed skim feeding on a large scale only on the evening of 18 August, approximately 32 km NNW of Pullen Island in 25 m water depth. About 20 to 30 whales in the 25 km^2 area were all engaged in apparent feeding. They had mouths open and were travelling slowly, usually just below the surface (approx. 2-3 m). Food availability on this occasion is described in the 'Feeding Areas' section (Griffiths and Buchanan 1982). On 23 and 24 August 1981 we saw one isolated example on each day of a whale feeding at the surface briefly (observed for less than 1 min) in approximately the same area as on 18 August.

Frequently the skim-feeding whales swam in echelon formation, each whale swimming just behind the preceding whale, but offset laterally by one-half to three body widths, reminiscent of geese in V formation. At other times, they swam abreast and parallel to one another. An analysis of videotape sequences



of this echelon feeding on 18 August 1981 showed that whales were a mean of 0.53 whale lengths (s.d. = 0.599, n = 66), or about 8 m, apart within the echelons. The mean distance to the nearest neighboring echelon on this day was 3.81 whale lengths (s.d. = 2.148, n = 9), or about 57 m. These distances were measured from different echelons or from the same echelon at intervals of at least 5 min. We videotaped a recognizable whale almost continuously for almost 3 h on this day as it skim fed in changing echelon formations, usually taking the lead position. Details of this observation are presented in the 'Disturbance' section (Fraker et al. 1982: Appendix 6).

Echelons of feeding whales were, in general, larger on 18 August 1981 than in 1980. While the largest such formation observed in 1980 contained five individuals, the largest in 1981 contained 14 animals. In 1981, the mean 'undisturbed' echelon size was 4.7 animals (s.d. = 4.05, n = 23). During 1980, all echelons were observed when our aircraft flew at a low altitude of about 300 m, and thus could have disturbed the whales.

We suspect that echelon feeding increases the feeding efficiency of those animals staggered behind and to the side of other individuals, perhaps by helping them to catch prey that escape or spill from the mouth of the whale in front. Skim feeding in echelon may allow more effective exploitation of concentrated patches of small prey than would be possible if whales were feeding alone. If so, the change in efficiency that accrues when echelon sizes change may have an important cost/benefit effect on energy expended per whale. This highly coordinated activity merits further study.

Typically, the skim-feeding whales were oriented with their backs at the water's surface. However, occasionally they swam on their sides with mouths open at an angle of about 60°, and once we saw two whales separated by three body widths swimming on their sides, belly to back. In one instance, a whale swam on its back for at least 3 min, with the underside of its chin at the surface.

During this study, observers in aircraft were not able to detect localized, dense patches of plankton at the surface. In contrast, Watkins and Schevill (1976, 1979) saw northern right whales skim feeding at the surface on patches of plankton that were visible to observers in aircraft;

these right whales appeared to adjust their courses to remain within the densest parts of the patches. Although we did not see broad patches of dense plankton, we saw linear concentrations of what was probably zooplankton, apparently along boundaries or 'fronts' between water masses (see 'Feeding Areas' section, Griffiths and Buchanan 1982). Although bowheads occasionally were seen near these linear concentrations, none were observed to feed along the 'front'. On one occasion, a lone bowhead passed at right angles through a 'front', but it made no attempt to swim along it.

Mud Tracking

Mud tracking occurs when whales swimming in shallow water (<12 m depth) disturb the bottom sediments with each fluke beat, producing clouds of mud joined by a narrower trail of muddy water. These clouds of mud were distinctly different from the mud clouds produced in bottom feeding. Although we often could not see the whales, in at least a few instances their mouths were open. We saw mud tracking only during three flights in the third week of August 1980 (see Table 1).

The significance of mud tracking is not clear, but we suspect that it is a mode of feeding. In at least some cases, it may represent incidental disturbance of bottom sediments by a whale that is water-column (or skim) feeding near the bottom in shallow water. We saw no evidence that bowheads ever turned and swam back along a mud track made previously. The mud tracks tended to be straight and some extended for well over 1 km. At certain times, clouds of mud streamed from the whale's body as it swam near the surface. In this case we suspect that the whales had contacted the bottom and that the mud had stuck to their bodies. Sometimes mud-tracking whales exhaled while submerged, producing a characteristic burst of bubbles (see 'Underwater Blow').

Salinity Gradient as a Possible Food Concentrating Mechanism

Our data on feeding behavior and characteristics of feeding areas (Griffiths and Buchanan 1982) suggest that an important phenomenon related to the hydrographic structure of the water leaving the Mackenzie River may be acting as a concentrating mechanism for the food of bowheads. The fresh water coming out of the river tends to over-ride the more saline ocean water, confining marine prey species to a wedge near the bottom. In recent years work on a variety of baleen whale species has shown that they employ an impressive array of techniques to concentrate their prey, and that concentration of prey may be as important to filter feeders as finding it in the first place (Nemoto 1959, 1970).

These concentration techniques include bubble nets, clouds of bubbles, rows of bubbles, echelon feeding in pairs, trios, etc. (e.g., Jurasz and Jurasz 1979; Hain et al. 1981). In gray whales there is now evidence that the entrances of breeding lagoons may serve as concentration areas for prey species that go close to the bottom to avoid strong outflowing tidal currents (Norris et al. in press). There is little tide in the Beaufort Sea, but the interaction of salt and fresh water in estuaries and adjacent areas, like those near the mouth of the Mackenzie River, may prove to be another means of concentrating prey. Further discussion of food availability appears in Fraker and Bockstoce (1980) and the 'Feeding Areas' section of this report (Griffiths and Buchanan 1982).

Underwater Blow

The underwater blow is a burst of air emitted underwater; it consists of bubbles of many sizes. The total bubble burst is circular and about 2-5 m in diameter when it arrives at the surface, but it quickly grows to show a white area of disturbance up to 15 m in diameter. Release of air underwater was recorded about 10 times via nearby (<1 km away) sonobuoys; the noise lasted about 3-4 s, but the white water and expanding concentric wave created by the blow were visible much longer. On one occasion the air was definitely seen to exit from the blowhole rather than the mouth. We presume that the whales exhaled forcefully and sharply underwater to create the disturbance. The underwater blow can occur at any time while the whale is under water; we saw it immediately after whales dove and just before they surfaced, but more usually at some time in the middle of the dive, when the whales were out of sight.

Occurrence of frequent underwater blows seemed to be associated with periods of pronounced feeding activity. During 1980, the number of observations of whales exhaling underwater increased abruptly on 19 August (Fig. 5). This was also the first day during which we observed almost all whales mud tracking in shallow water just below the surface. The next day, during the first flight of 20 August, we observed similar but not as widespread mud-tracking behavior, and the incidence of underwater blowing was also somewhat lower. On 21 August whales remained at the surface for brief periods, and much underwater blowing occurred; it is possible that whales were water-column feeding during this day. On 23 August, skim feeding occurred and the frequency of underwater blows was also higher than the 1980 mean, which was 5.2 blows/observation hour. In 1981, the highest incidence of underwater blowing occurred during the evening of 18 August during the one 1981 flight when much subsurface skim feeding was seen (Fig. 5).

Because underwater blows rarely could be ascribed to a particular individual for which we had behavioral data, we cannot directly compare the relative frequency of underwater blowing in feeding and non-feeding whales. But the coincidence of high underwater blow rates with strong evidence of feeding strengthens our original suspicion that this phenomenon is in some way related to feeding. Furthermore, we witnessed less feeding in 1981 than in 1980, and there were fewer underwater blows in 1981 than in 1980 (1980, 158 blows seen in 30.4 observation hours; 1981, 57 blows in 30.8 observation hours; chi-square = 48.77; df = 1; $p \ll 0.001$). This behavior occurs often both when whales are skim feeding at or near the surface and when they are mud tracking. This is consistent with the view that mud tracking may be a method of subsurface skim feeding in which the whales roil up mud as they move forward in very shallow water.

Underwater blowing occurred more often in the morning and evening than around the solar midday (about 15:00 MDT) in both years (Fig. 6). The midday low point in underwater blowing coincides with a peak in the frequency of socializing, the main non-feeding behavior observed (see 'Social Behavior', below). Nemoto (1970) suggested that baleen whales in general show a high level of feeding activity in the morning and a lower level during midday.

During 1980, underwater blowing was more frequent in shallow (less than 14 m) than in deeper (20-40 m) water (Fig. 7). In 1981, when we made

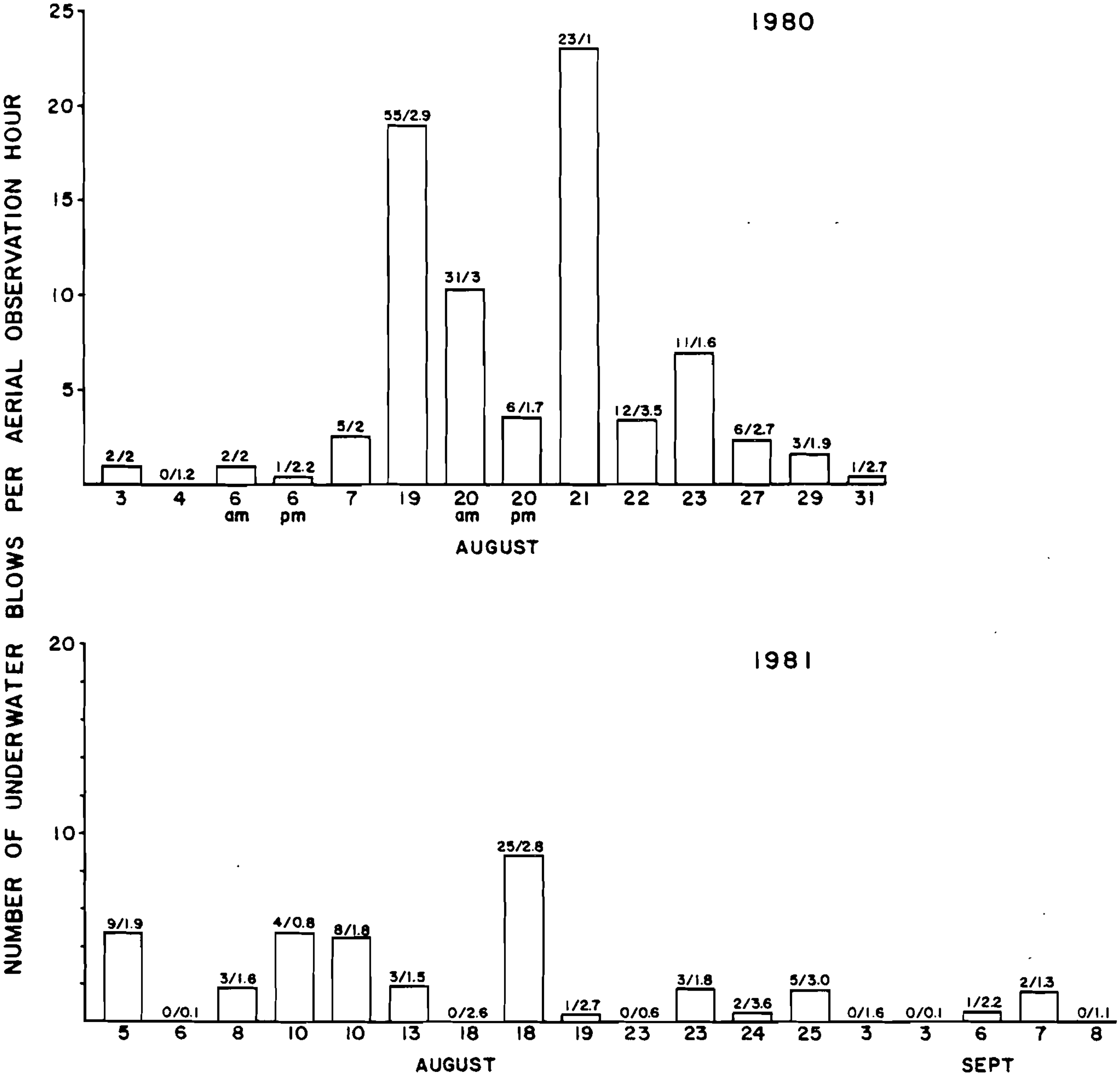
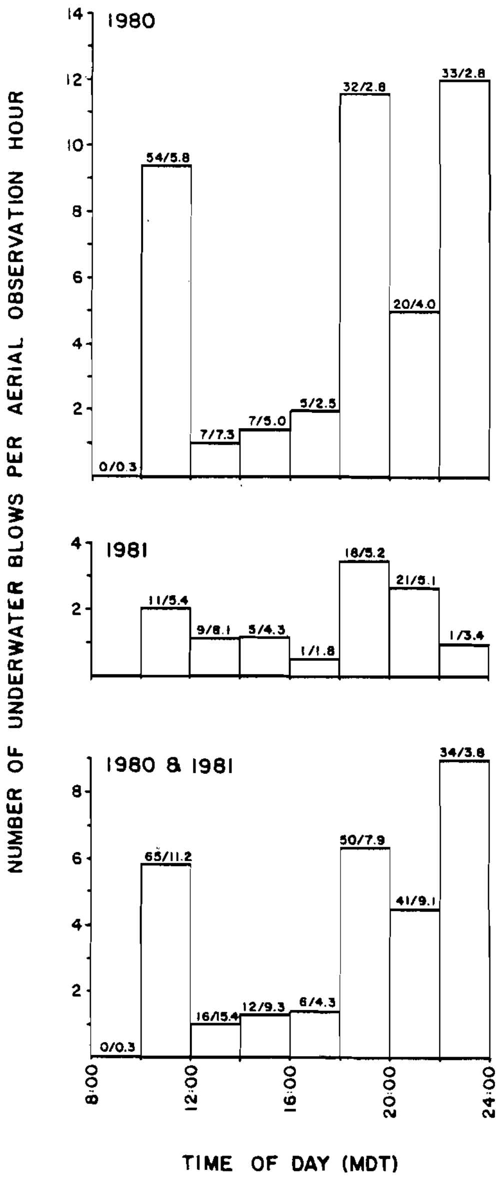


FIGURE 5. Number of underwater blows per aerial observation hour during each airflight, 1980 and 1981. The numbers at the top of each column are number of blows seen/number of observation hours.



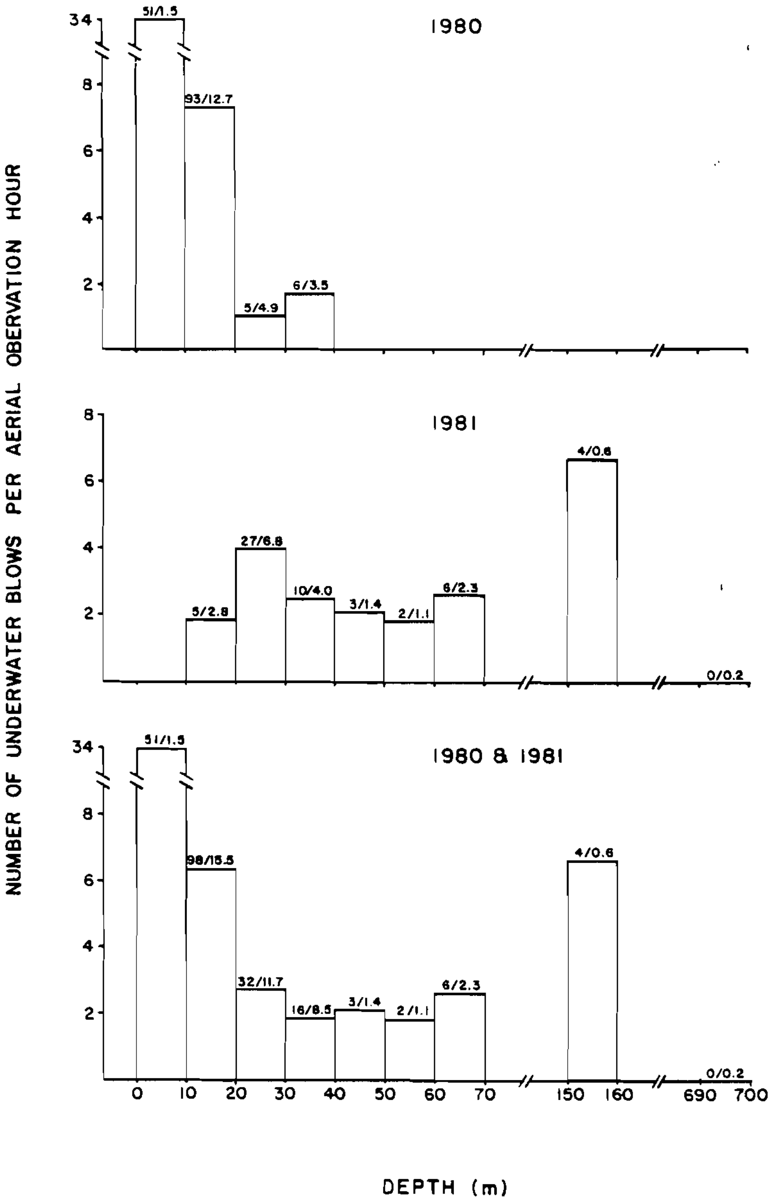


FIGURE 6. Number of underwater blows per aerial observation hour in relation to time of day in 1980, 1981 and both years combined. Presentation as in Figure 5.

FIGURE 7. Number of underwater blows per aerial observation hour in relation to water depth in 1980, 1981 and both years combined. Presentation as in Figure 5.

behavioral observations on whales in water less than 20 m deep only once (on 25 August), there was no obvious relationship between frequency of underwater blows and water depth. In 1981 several underwater blows were observed in water 150-160 m deep (Fig. 7) near the southern edge of the offshore pack ice.

We have not included underwater blows in our listing of possible feeding techniques; there is at best only a general similarity to bursts of bubbles associated with feeding humpback whales in the North Atlantic (Hain et al. 1981). It is not certain if or how the air released by bowheads is useful for catching or concentrating prey. We saw no indication that bowheads turned to swim back through the location of an underwater blow. As noted above, however, there is circumstantial evidence of some form of association between underwater blowing and feeding.

Synchrony of Behavior

On many occasions there was an impressive degree of synchrony of basic behaviors among members of quite widely spaced groups. We observed apparent synchronization of behaviors on time scales ranging from seconds to days.

Synchrony in General Activity

During 1980, on a time scale measured in days, we found that all or almost all animals in a particular area usually were doing essentially the same thing for up to several days. Some days later the whales were sometimes gone from that area, and whales were then found elsewhere engaged in different activities (Table 1).

We made our first observations of bowheads in 1980 during the first week of August (3 and 5 August). These whales were generally north and east of Issungnak artificial island and were mainly engaged in water-column feeding--diving for relatively long periods where turbid Mackenzie River water overlay the denser saline water of the Beaufort Sea. We frequently saw whales defecate during this period. By 6 and 7 August, whales in this general area shifted to more surface-active behavior, with groups of animals close together and individuals interacting by pushing each other and by apparent chases. We saw little defecation at this time. On 12 August, at least 15 animals about 30 to 40 km west of this group were all apparently bottom feeding.

In the third week, whales were encountered in two additional areas: east of Pullen Island (19 and 20 August 1980) and just west of McKinley Bay (19-22 August 1980). In the Pullen Island group, all whales were mud tracking as described above. In the second area, mud churning was evident, but there was much less underwater blowing. Some animals, but not all, had mouths open at the surface.

Early in the fourth week in August 1980 (22 and 23 August), almost all whales we encountered were skim feeding in groups of 10 to 30 animals north of McKinley Bay. On the same days, skim feeding was also reported by Renaud and Davis (1981) in hundreds of animals spread over a much larger area north of the Tuktoyaktuk Peninsula. However, in the general Issungnak area there were still substantial numbers of whales that were water column feeding.

At the end of August 1980 (27, 29, and 31 August), whales spent more time at the surface and interacted in small groups of 2-5 individuals. Also during this period, such small groups were sometimes oriented toward the SSW, perhaps indicating the beginning of migration.

In summary, during 1980 we encountered a series of behavioral events, with whales in an area doing much the same thing for up to approximately five days. During 1981, however, there was no clear pattern to the behaviors observed (Table 2). A partial explanation for the synchrony of behavior seen in 1980 may be that whales moved to exploit new food resources, and that the most appropriate feeding mode changed according to site-specific conditions.

Synchrony in Dives and Surfacings

While observing bowhead whales from the air, we sometimes had the impression that all the whales in an area were synchronizing their surfacings and dives. Furthermore, many of these were too spread apart to have been in visual contact and were presumably synchronizing their behavior acoustically. None of the data that we collected in 1980 were appropriate to test this hypothesis, so in 1981 we tried to obtain more information on this kind of synchrony.

On 8 occasions during 4 days in 1981, we recorded time series data on the number of groups of whales (regardless of group size) at the surface in the area under observation from the aircraft. Groups were defined as whales within five adult body lengths of one another (about 75 m), a distance which assured that animals in different groups were not in visual contact. Any synchrony observed might therefore be the result of acoustic communication. The number of groups visible at the surface was counted every 20 or more seconds, the length of time required for the aircraft to complete a circle around the observation area. We tested the resulting data by scoring each count as an increase or decrease from the previous count (ignoring repeated observations of the same value) and then doing a runs test on the trends. In no cases were there significantly fewer runs than expected by chance (a result that would have indicated synchrony), and in two cases there were significantly more runs than expected by chance.

Although we have not been able to substantiate statistically our impression of synchrony, we were certain that it does occur. Ljungblad et al. (1980b) also reported synchrony among whales engaged in water-column feeding in an area about 75 km east of Kaktovik, Alaska. They reported that "...whales were observed on the surface almost at regular intervals and gave the impression of resting between dives; then, suddenly, no whales would be seen in any quadrant for several minutes."

Synchrony in Orientations

Analysis of the orientations of whales spread over large areas provides additional evidence that groups of whales at times synchronize their behavior. The best data that we collected to test for non-randomness in orientation were the observations from two of the systematic survey flights in 1980 and part of the 31 August 1980 flight when we were flying in a straight line. At these times we were sure that we counted each individual only once. Rayleigh tests and chi-square tests of these observations show that the whales chose orientations that were significantly non-random (Table 3).

Table 3. Bowhead orientations, judged relative to true north from the air. Only during the direct flights was each observation known to represent different animals. During the circling flights, each whale was scored an unknown number of times (but only once per surfacing). All observations were of presumably undisturbed animals.

	# of animals with these orientations									Vector mean direction	Rayleigh test*	chi-square test* P
Date	N	NE	E	SE	S	SW	W	NW	total			
DIRECT FLIGHTS												
11 Aug 1980	16	1	3	0	5	2	10	6	43	321°	<0.001	<0.001
12 Aug 1980	7	5	16	5	7	6	9	2	57	bimodal	n.s.	<0.025
31 Aug 1980	1	1	1	3	8	8	0	1	23	189°	<0.001	/
CIRCLING FLIGHTS												
31 Aug 1980	4	4	6	3	11	1	0	2	31	121°	<0.05	/
10 Aug 1981	0	3	0	2	0	4	0	1	10	-	n.s.	/
10 Aug 1981	3	1	7	2	1	6	0	1	21	bimodal	n.s.	/
13 Aug 1981	12	9	11	1	1	0	1	1	36	43°	<<0.001	/
18 Aug 1981	2	5	10	5	6	1	2	1	32	111°	<0.001	/
18 Aug 1981	3	0	0	0	0	1	6	0	10	289°	<0.005	/
23 Aug 1981	0	4	1	1	0	0	0	0	6	62°	<0.02	/
24 Aug 1981	1	0	3	2	5	8	10	5	34	243°	<0.001	/
6 Sept 1981	1	7	2	1	0	2	3	3	19	-	n.s.	/
7 Sept 1981	2	5	1	1	0	2	2	3	16	-	n.s.	/
8 Sept 1981	1	8	3	1	1	0	0	0	14	62°	<0.001	/

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* In both the Rayleigh and chi-square tests, the null hypothesis is that the orientations are random. The alternate hypothesis in the Rayleigh test is that there is a single 'preferred' direction (Batschelet 1972), whereas the alternate hypothesis in the chi-square test is more general--that the orientations are non-random. (During some of the flights, the data were collected in degrees true to the nearest 10° instead of the eight compass directions, and the Rayleigh tests were done on the original data.)

/ means cell sizes too small for a chi-square test.

For the flights when we were circling over certain areas to make detailed behavioral observations, we analyzed the orientations using the first heading noted for each surfacing of a whale. Because we were making repeated observations on the same animal in some cases, any consistency in orientations during those flights is attributable in part to different whales and in part to subsequent surfacings of the same whale. There were 10 flights in 1981 and one in 1980 with enough data for such an analysis on undisturbed whales. During seven of the flights the whales were oriented significantly toward a single direction (Table 3). The headings changed from day to day, however, and bore no apparent relationship to the activity of the whales.

The headings on the latest day on which we made observations in each year usually were not in the direction to be expected at the beginnning of the westward migration. On 31 August 1980, bowheads observed while we were circling in waters north of the Tuktoyaktuk Peninsula were oriented toward the southeast (121° T). However, later that day on a direct flight, we found other bowheads to be significantly oriented toward the south (189° T). In this same general area, Renaud and Davis (1981) also recorded an eastward tendency for bowheads seen on 21-24 August 1980, but a significant southwestward tendency (236° T) on 3-4 September 1980. On 8 September 1981, whales west of Herschel Island were oriented toward the northeast (62° T), again not the direction to be expected at the beginning of westward migration. These results support our impression that most of the whales we observed were not migrating.

We do not know whether these consistent orientations represented a type of social synchrony or whether the whales independently reacted to environmental stimuli (such as currents or wave orientations). Norris et al. (in press) observed gray whales that may have been feeding by stationing themselves against the current in a bay in Mexican waters, and Shane (1980) has reported a similar stationing against the current for bottlenose dolphins in Texas. Gray whales in lagoons have been observed to move in the same direction as the tidal current (Norris et al. 1977), but in that case movement may have been related to avoiding shallow water as the tide receded.

Individually Distinguishing Features

Bowhead whale adults are mainly black, with white chin patches which lie mostly below the waterline while the whales are at the surface, but which can be seen partially from the air. Distinctive variations from this color pattern sometimes permit the recognition of individual whales. Southwell (1899) reports whalers' observations of distinctively marked bowheads returning to the same locations in subsequent years. Identification of individuals has been a key to making significant advances in the study of the biology and behavior of a number of other cetacean species (Darling 1977; Würsig 1978b; Katona et al. 1979; Payne et al. 1981), so we attempted to identify individuals whenever possible.

A few bowheads had dramatically larger chin patches than the majority, and on one occasion, one such animal in a small group could be reidentified upon subsequent surfacings. Because many whales in the population appear to have similar chin patches, this trait cannot be used alone to reidentify individuals over long periods.

Some bowheads exhibit a diffuse ring of gray or white around the peduncle, or tailstock, just anterior to the tail flukes. Others, less commonly, have various amounts of white on the dorsal surface of the tail. There are also often small white spots and lines on different parts of the back. The locations of these white pigmentation patterns may be used to identify whales, at least over short periods (within a single observation session), and over longer times if good photographs are obtained. One noteworthy case of reidentification of a group of distinctive bowheads after about 2 wk is described in the 'Social Behavior' section, below. During the present study we were hampered in obtaining clear photographs by the airplane's high altitude (usually 457 m or more) and, in 1980, by the absence of a window that could be opened for photography. Lower altitudes can be used only if disturbance of the whales is acceptable. Because of other priorities, we made no serious effort to obtain high resolution vertical photographs of bowheads, but that approach proved successful in recording individually recognizable animals during a separate but simultaneous study in the same area in 1981 (Davis et al. 1982).

One bowhead, seen on 3 August 1980, was identified by a yellow rope that was attached just in front of the blowhole on the right side of the head and extended to more than one whale length behind the animal. This animal had probably been harpooned on the Alaskan whaling grounds and had made its way to the eastern Beaufort Sea with other migrating whales. It was easily and unmistakably reidentified upon subsequent surfacings. We noted two peculiarities in its behavior. First, it repeatedly turned to its left, describing a semi-circle while at the surface during 4 of 5 surfacings. It never interacted in any obvious way with another whale. By way of comparison, we saw 27 surfacings of the 5-8 other whales in the immediate area during the same period. In only 7 of these surfacings did the whale turn at all, and all but 3 of the turns (11% of the surfacings) were obvious interactions with another whale. Furthermore, of the 8 turns made by the other whales (1 whale made 2 turns in a single surfacing), half were clockwise and half counterclockwise. The second peculiarity of the harpooned whale was that during all 3 of its dives that we could see well, the animal failed to lift its flukes out of the water. For comparison, of the 28 closely observed dives by other whales in the same period, only 4 dives were not accompanied by raised flukes. We computed the mean interval between blows for the harpooned whale and found it to be 10.4 ± s.d. 2.55 s ($n = 17$), which was shorter than the means both for the other whales in the area that day (12.2 ± s.d. 6.73 s, $n = 107$) and for all other whales seen in this study (13.0 ± s.d. 8.38 s, $n = 2067$). In both cases the difference was statistically significant ($t' = 2.01$, $p<0.05$, and $t' = 3.98$, $p<0.001$, respectively; t' is the t statistic for heterogeneous variances--Sokal and Rohlf 1969). We conclude that the movements and respiration patterns of the harpooned whale were abnormal.

The bodies of many bowheads exhibit large areas of slightly gray patches that can be seen from the air only in good photographs or with binoculars. These patches are probably areas of recently-sloughed skin, as in southern right whales (Payne et al. 1981), where such patches change rapidly, even on a daily basis. They can be used with difficulty during observations within one day, but--if the analogy with right whales is correct--not over a longer term.

Bowheads may also have white blazes or spots on their ventral surfaces. In the present study, only one feeding whale and two breaching ones showed the ventral surface, and thus identification by ventral blazes was not possible. One of the breaching whales had such a ventral mark.

Respiration and Surfacing Characteristics

Four characteristics of a surfacing lend themselves to repeated quantitative sampling. The blow interval, number of blows per surfacing, surface time (length of surfacing), and down time (length of time between surfacings) were measured 2067, 270, 319, and 115 times, respectively, for presumably undisturbed whales. These results are discussed in some detail. Because the variables involved are comparatively easy to assess quantitatively, they are suitable for use in analyses of responses to disturbance. A detailed understanding of respiration and surfacing behavior under undisturbed conditions is a prerequisite for interpretation of the disturbance responses.

Figures 8 to 11 present the frequency distributions of all observations of these four variables under presumably undisturbed conditions in each year. The distribution of down time (Fig. 11) is very highly skewed; over half of the dives had durations <1 min, but dives as long as 17 min were recorded. The down time distribution is also affected by sampling bias: we were less likely to record long than short dives because of the difficulties in keeping track of recognizable individuals and following the movements underwater of animals we couldn't see. Because of the skewed distribution of down times, we have not provided 95% confidence intervals for the means of this variable and have applied only non-parametric statistical tests. Figures 12 to 15 summarize the distribution of each of these variables for each of our observation flights. Again only the data collected during presumably undisturbed conditions are included. Table 4 presents the summary statistics for each of these variables.

Blow Intervals

The interval between blows within a single surfacing was the most constant of the four variables among dates (Fig. 12), and the means for the

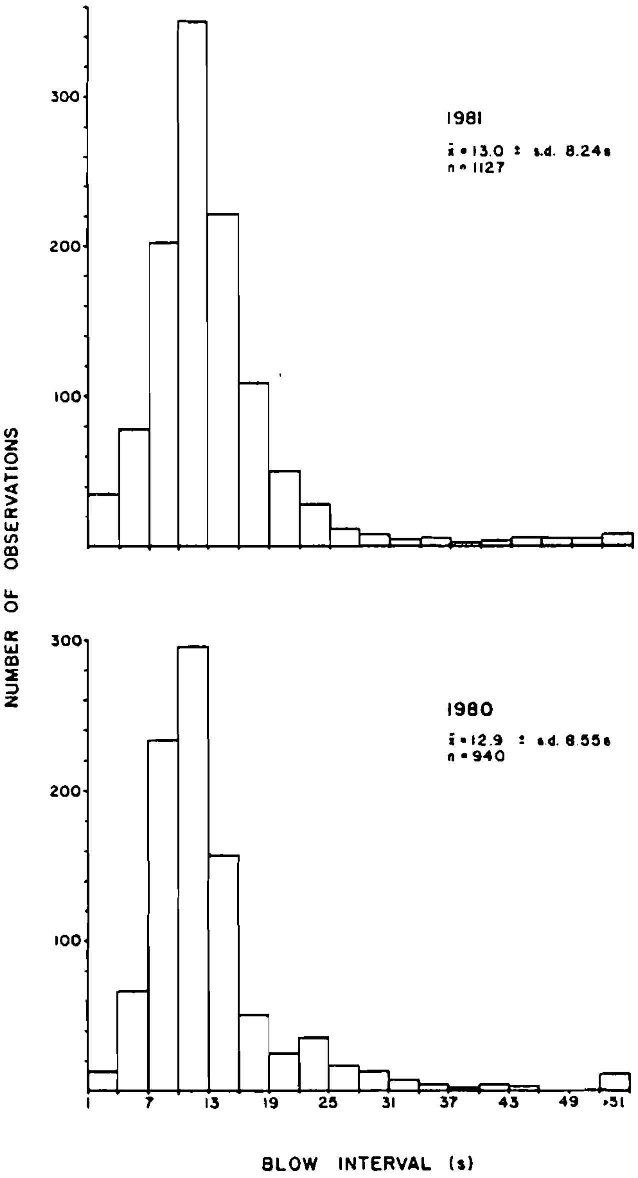


FIGURE 8. Frequency distribution of blow intervals observed in 1980 and in 1981.

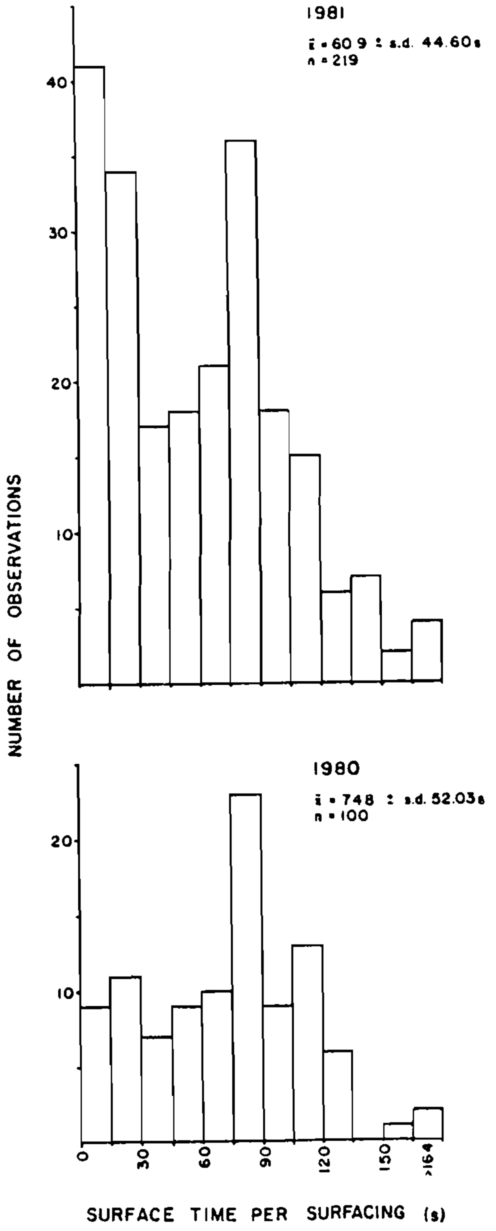


FIGURE 9. Frequency distribution of length of surfacings in 1980 and in 1981.

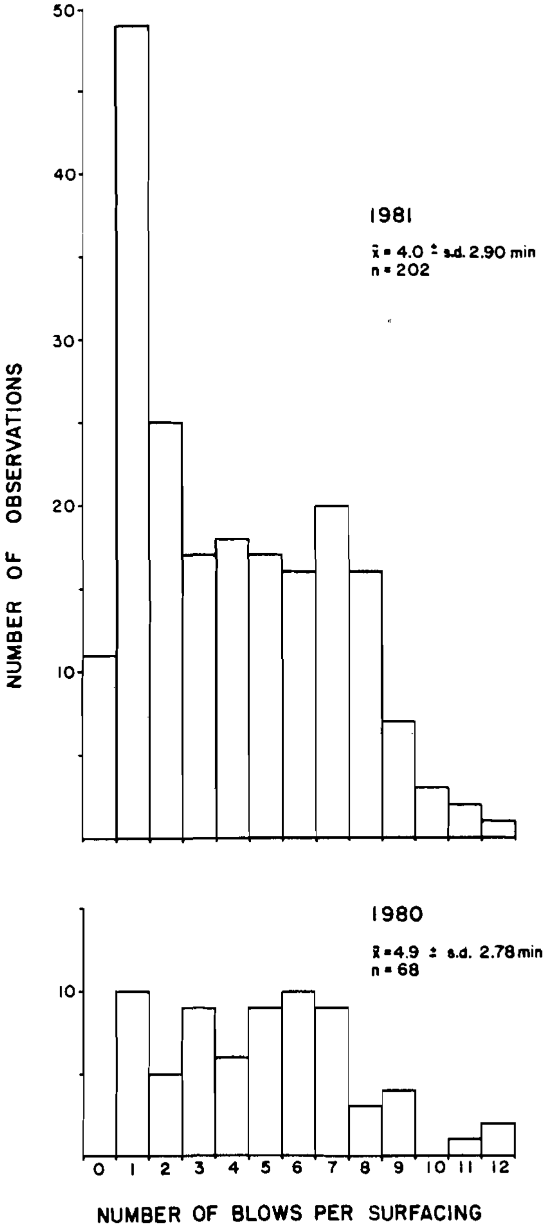


FIGURE 10. Frequency distribution of number of blows per surfacing in 1980 and in 1981.

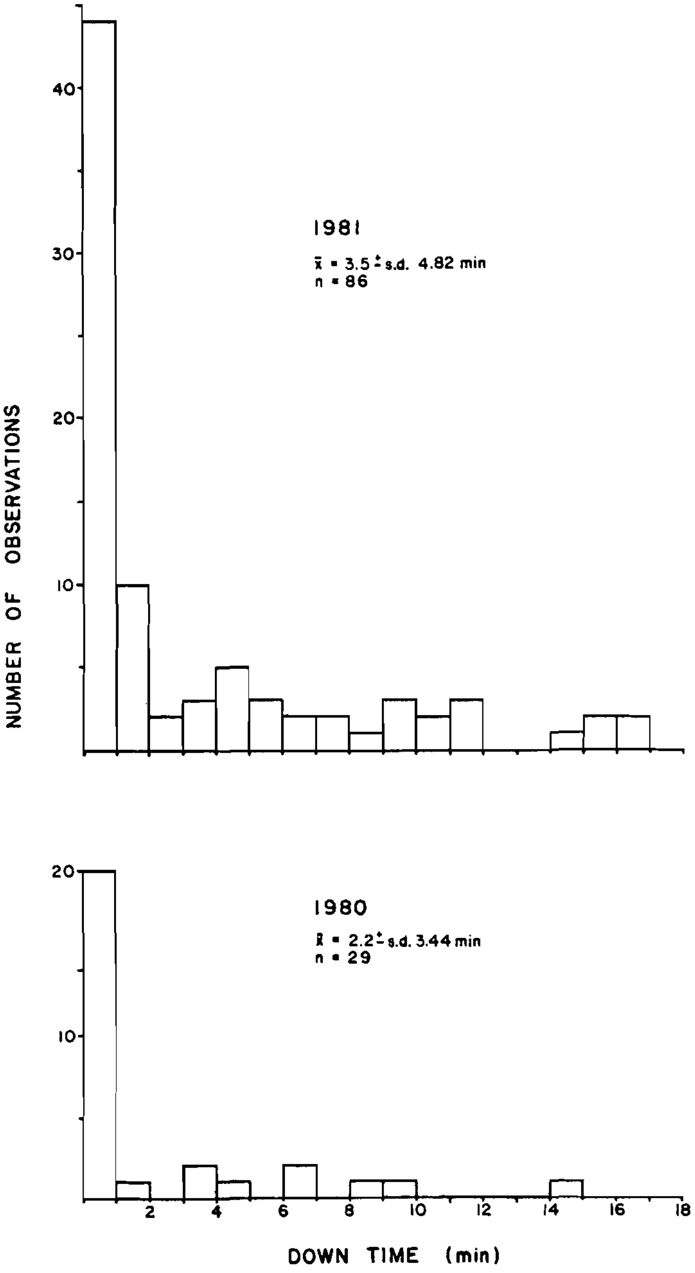


FIGURE 11. Frequency distributions of length of dives in 1980 and in 1981.

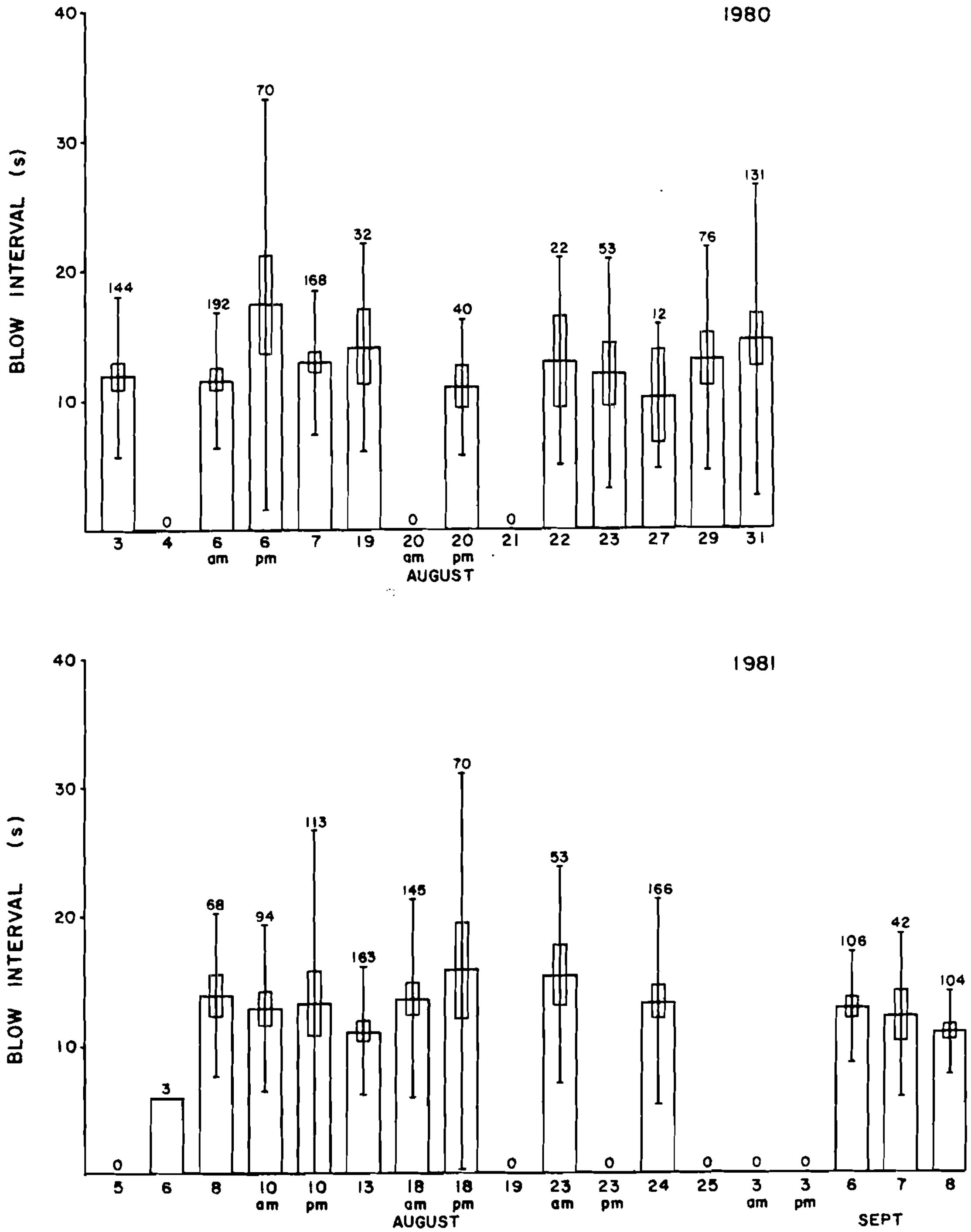


FIGURE 12. Mean interval between blows during each airflight in 1980 and in 1981. The vertical line in each column represents one standard deviation on either side of the mean, the box represents the 95% confidence interval for the mean, and the number is the sample size.

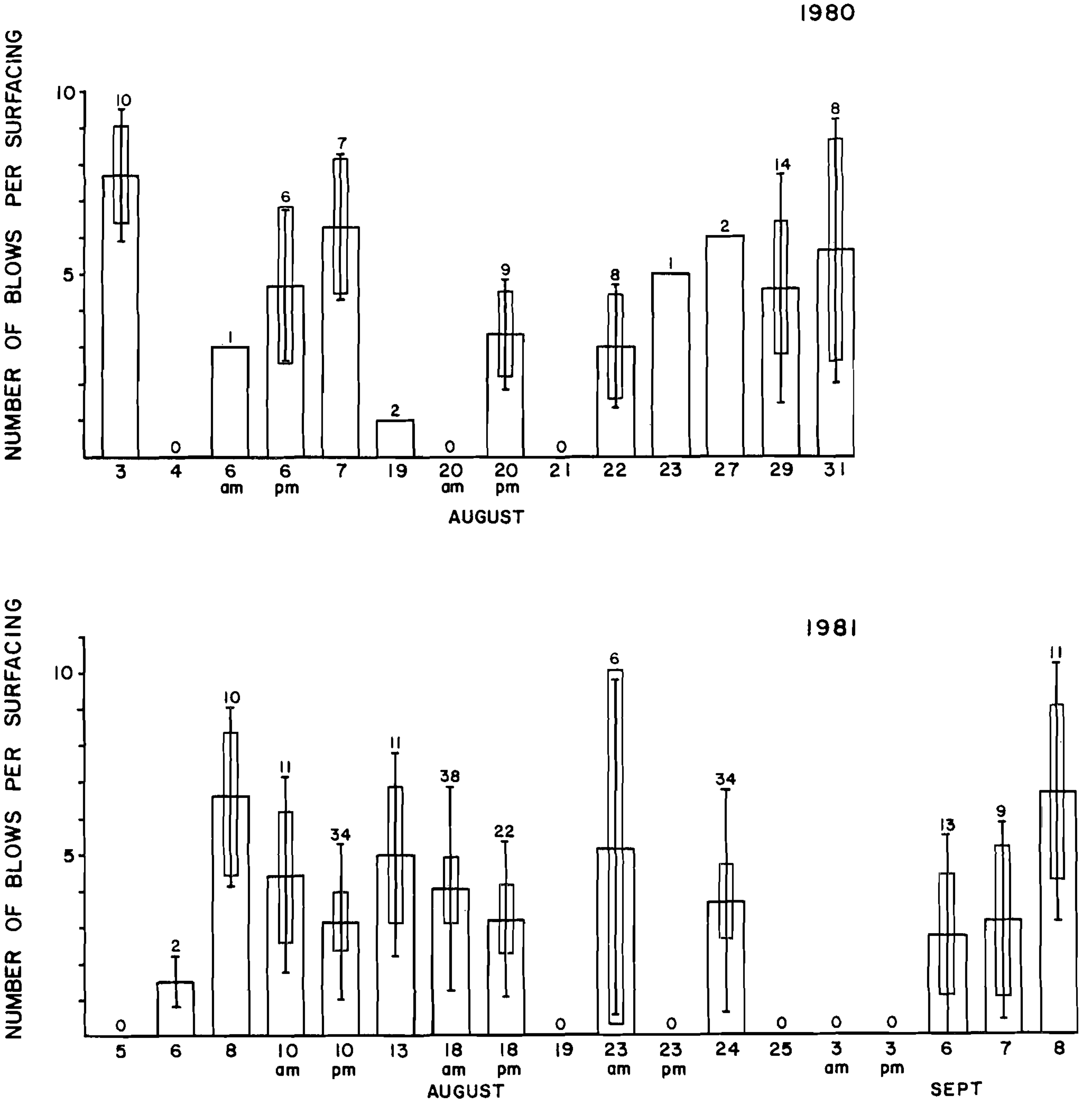
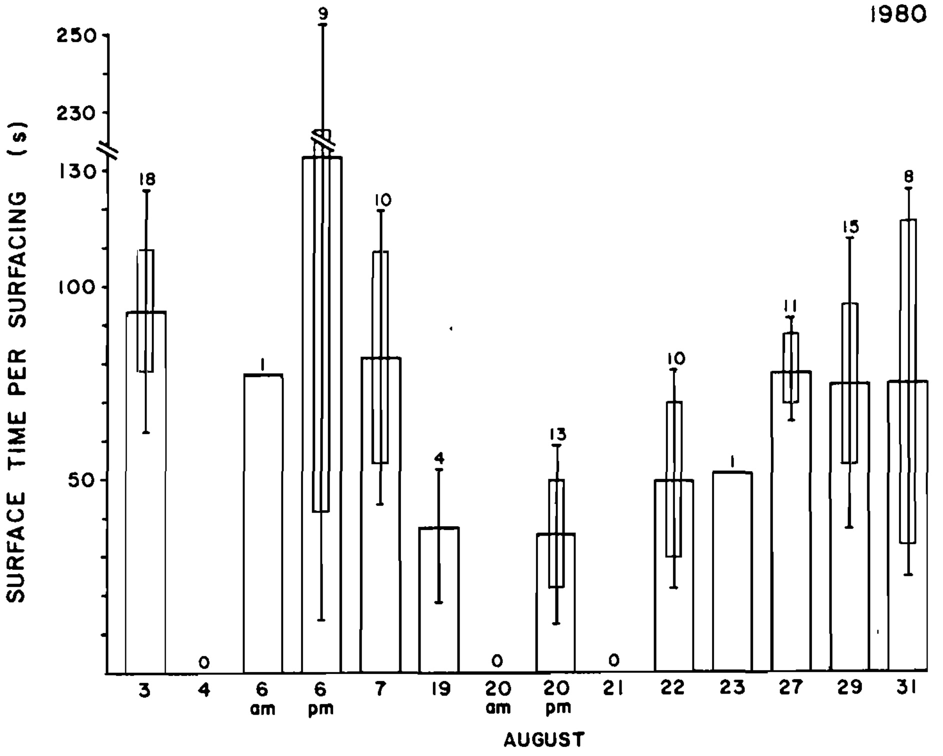


FIGURE 13. Mean number of blows per surfacing during each airflight in 1980 and in 1981. Presentation as in Figure 12.



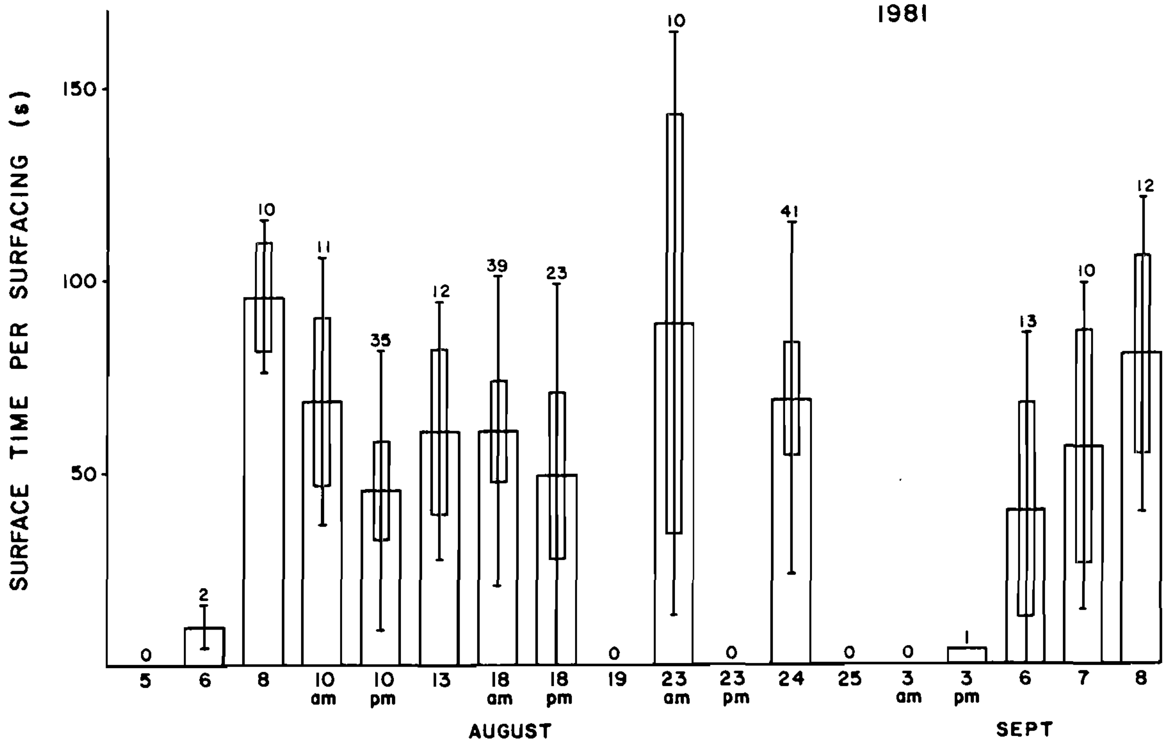


FIGURE 14. Mean time at surface per surfacing during each airflight in 1980 and in 1981. Presentation as in Figure 12.

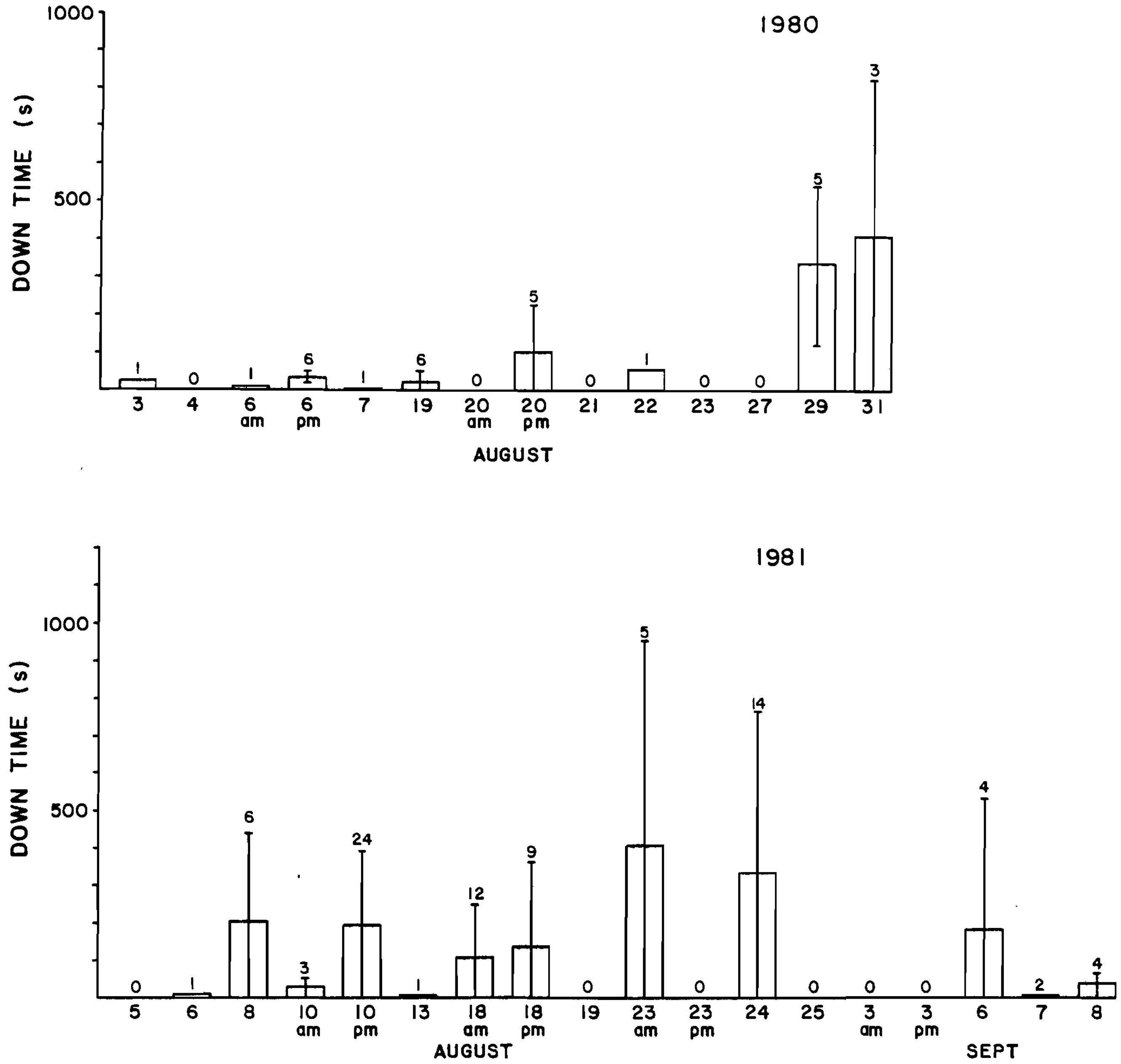


FIGURE 15. Mean down time during each airflight. The vertical line in each column represents one standard deviation on either side of the mean and the number is the sample size.

two years were nearly identical (Table 4), despite the considerably different frequencies of feeding and social behavior in the two years (overall mean = 13.0 ± s.d. 8.38 s, n = 2067, range 1-113 s). In comparison, Koski and Davis (1980) found that bowheads of the Davis Strait/Baffin Bay population migrating along the coast of Baffin Island in the autumn of 1979 had a blow interval of 16.11 ± s.d. 8.29 s (range 4-68 s; median = 14 s; n = 399 blows by 31 whales). The difference in blow intervals between whales migrating past Baffin Island in autumn and those that we observed engaged in other activity in the Beaufort Sea during summer is highly significant ($t = 6.80$, df = 2464, $p \ll 0.001$).

Blows per Surfacing and Duration of Surfacing

The mean number of blows per surfacing (Fig. 13) and the mean time at the surface per surfacing (Fig. 14) were more variable among dates than was the mean blow interval. While some of this variability may be a reflection of smaller sample sizes, we believe that these two characteristics are in fact more variable than blow interval. Due to the relative stability of blow intervals, the number of blows per surfacing and the surface time are very highly correlated ($r = 0.718$, $t = 16.89$, df = 268, $p \ll 0.001$).

During 1980, both blows per surfacing and surface times were lower during the middle of August than during the beginning and end of August. The decrease in mid August occurred during the time when whales were feeding with open mouths at or just below the surface. Although we recognized too few individual whales to allow collection of many dive times, we received the impression that surface-feeding whales dove more often and thus reduced the length of the periods spent at the surface, but that they surfaced very quickly again. We do not know why these brief surfacings are interspersed with relatively brief dives. Each one may represent the end of a feeding run; the whales closed their mouths for unknown reasons and submerged briefly before beginning to surface again.

In 1981, the number of blows per surfacing and the time at the surface per surfacing are again closely related by date because of the relative invariability of blow intervals. The data are not as clearly related to

Table 4. Summary statistics for the principal surfacing, respiration and dive variables in presumably undisturbed bowheads.

	Blow Interval (s)			Number of blows per surfacing			Surface time per surfacing (min)			Down Time (min)		
	x	s.d.	n	x	s.d.	n	x	s.d.	n	x	s.d.	n
All whales 1980	12.9	8.55	940	4.9	2.78	68	1.25	0.867	100	2.22	3.442	29
1981	13.0	8.24	1127	4.0	2.90	202	1.02	0.743	219	3.50	4.823	86
1980 + 1981	13.0	8.38	2067	4.2	2.90	270	1.09	0.790	319	3.17	4.535	115
Calves	13.4	9.21	61	1.5	1.99	14	0.69	0.552	20	1.28	1.588	9
Adults with calves	15.8	8.56	132	3.5	2.70	17	1.15	0.948	21	6.90	7.522	15
All others	12.8	8.30	1874	4.4	2.88	239	1.11	0.787	278	2.75	3.763	91
Socializing whales	14.0	10.54	426	3.9	2.46	58	1.11	0.762	70	2.69	3.213	28
Non-socializing whales	12.7	7.70	1641	4.3	3.01	212	1.06	0.755	249	3.33	4.890	87
Skim feeders	15.0	12.09	83	2.9	2.23	13	0.68	0.641	14	2.35	3.478	11
Water-column feeders	12.0	5.01	175	6.8	2.31	17	1.56	0.658	25	10.31	6.800	2
Non-feeding whales	12.7	7.62	1704	4.0	2.90	223	1.03	0.784	261	3.01	4.493	100
Depth (m) 0-15	12.5	6.97	94	2.9	1.62	19	0.67	0.406	27	1.02	1.425	12
16-30	13.2	10.04	539	4.8	2.93	61	1.17	0.675	78	4.09	4.413	17
31-60	12.7	7.44	951	3.9	2.78	128	1.00	0.704	141	3.58	5.088	59
61-152	13.5	6.52	145	5.1	2.85	23	1.25	0.586	23	5.40	4.478	10

feeding as in 1980. Nonetheless, the number of blows per surfacing on the evening of 18 August 1981, when whales were feeding in echelon formations just below the surface, is comparable to that on the evening of 20 August 1980, when whales were in echelon formations at the surface.

Overall, the mean number of blows per surfacing was 4.19 ± s.d. 2.90 (n = 270, range 0-12). In contrast, Carroll and Smithhisler (1980) reported 6.53 ± s.d. 2.84 (n = 41) blows per surfacing during the 1978 spring migration of bowheads around Alaska. Similarly, Rugh and Cubbage (1980) reported 2-9 blows during most surfacings at Cape Lisburne, AK, in spring, (mean at least 6.38 per surfacing). Thus, the mean number of blows per surfacing appears to be somewhat less in summer than in spring.

In our study, the mean surface time per blow sequence for both years was 1.09 ± s.d. 0.79 min (n = 319, range 0.03-5.87 min). Davis and Koski (1980) found surface times of 0.2 to 6.0 min (mean 1.2, n = 16 surfacings by 5 whales) for bowheads in Baffin Bay during the fall migration of 1978, and Koski and Davis (1980) found surface times of 1.69 ± s.d. 1.01 min (range 0.02-6.25 min; n = 93 surfacings by 27 whales) during the fall of 1979. Carroll and Smithhisler (1980) reported the mean surface time during spring migration around Alaska to be 1.52 min, although this was determined in a somewhat indirect manner. Rugh and Cubbage (1980) report surface times per blow, but not surface times per surfacing. The available data suggest that surface times tend to be somewhat longer during migration than in summer. This is consistent with the somewhat larger mean number of blows per surfacing observed in spring than in summer.

Duration of Dives

Overall, dives between blow sequences lasted 3.17 ± s.d. 4.53 min (n = 115, range = 0.02 to 17.42 min), considering only occasions when the whales were presumably undisturbed. A dive of duration 26.8 min was recorded on 23 August 1981 during a period of potential drillship disturbance.

Because of small sample sizes, comparisons of dive times in different circumstances are difficult. Nevertheless, some consistent results were obtained (Fig. 15). When undisturbed whales were skim feeding at or near the surface on the evenings of 20 August 1980 and 18 August 1981, their mean down times were very similar and relatively short. On two days when water-column feeding was suspected, 29 August 1980 and 24 August 1981, the mean down times were similar and relatively long. Our suspicion that water-column feeding was occurring is in part founded on the occurrence of longer down times, and we cannot confirm that feeding was occurring below the surface out of sight. Thus the coincidence of down time with feeding mode is partly based on a circular argument.

Our results are not directly comparable to those of other workers because different observers define 'dives' differently. Braham et al. (1979) reported dives of durations 1.7 to 28 min during spring migration past Cape Lisburne, AK. Rugh and Cubbage (1980) and Carroll and Smithhisler (1980) divided dives of spring migrating whales off Alaska into short dives between long soundings, and the long soundings themselves. Rugh and Cubbage found that the short dives were 11.6 ± s.d. 2.40 s (n = 50), while Carroll and Smithhisler reported a similar 10.8 ± s.d. 5.20 s (n = 30). Long, or sounding, dives were quantified too infrequently for analysis by Rugh and Cubbage, but Carroll and Smithhisler reported values of 3.0-26.7 min with mean 15.6 ± s.d. 5.0 min (n = 63). Davis and Koski (1980) reported dives lasting 2 to 20 min (n = 16 dives by 5 whales, mean = 9.6 min) during the 1978 fall migration of the Davis Strait/Baffin Bay population, and Koski and Davis (1980) reported dive times of 8.65 ± s.d. 2.73 min (range 1.03-27.50, n = 88 dives by 29 bowheads) during the fall of 1979.

The dive times that we measured for summering whales were consistently lower than the means for migrating bowheads in Baffin Bay as reported by Davis and Koski (1980) and Koski and Davis (1980). The water in their study area, even directly below their coastal vantage point, was very deep. The briefer dive times found in the present study may be partially attributable to the shallower water depth, but they may also be attributable to our bias toward short dives because of the difficulty of reidentifying individual bowheads. Recognition of individuals was not a problem in the Koski and Davis (1980) study, where the number of individuals was very low and observation conditions were good. We cannot compare our dive time data with those obtained in Alaska in spring because short and long dives have been treated separately by most Alaskan workers.

Effects of Water Depth

To determine whether surfacing and dive characteristics changed with depth of water, we calculated product-moment correlation coefficients for length of surfacing, number of blows per surfacing, and dive time in relation to water depth. We also calculated mean values for each of these variables for whales in four categories of water depth (Table 4).

Surface times and blows per surfacing tended to be short in the shallowest water depths, but were unrelated to water depth when depth was >15 m. During 1980, length of surfacing was significantly correlated with depth ($r = 0.292$, $t = 2.88$, $n = 91$, $p<0.01$) (Fig. 16). During 1981, however, when we observed whales in deeper waters, no significant trend was evident ($r = 0.092$, $t = 1.23$, $n = 180$, $0.20<p<0.40$), nor was there a significant trend for both years combined ($r = 0.044$, $t = 0.72$, df = 269, $p>0.50$). During 1980 we also found a significant correlation between depth and number of blows per surfacing ($r = 0.272$, $t = 2.19$, $n = 62$, $p<0.05$), but not during 1981 or for both years combined. The similarity in results for these two variables was to be expected given the correlation between number of blows and surface time. As shown in Table 4, mean surface times and blows per surfacing were lower in waters ≤15 m deep than in deeper water, but there was no consistent trend across the next three depth categories (16-30, 31-60 and 61-152 m). Analysis of variance based on those four depth categories showed a significant depth effect for both surface times ($F = 4.96$, df = 3,267, $p<0.005$) and blows per surfacing ($F = 3.66$, df = 3,227, $p<0.025$), doubtless because of the shorter values in the shallowest depths.

Blow intervals were unrelated to water depth (Table 4; $F = 0.73$, df = 3,1725, $p>>0.1$).

The few dive times recorded in very shallow water were all short (Table 4), but there was no significant correlation between length of dive and depth of water during either year (Fig. 17). This is perhaps not surprising; because of the relatively shallow water, the distance to the bottom is short even in the deepest area where we measured dive durations (152 m). Indeed, most depths over which we watched whales were less than three times the length of a whale.

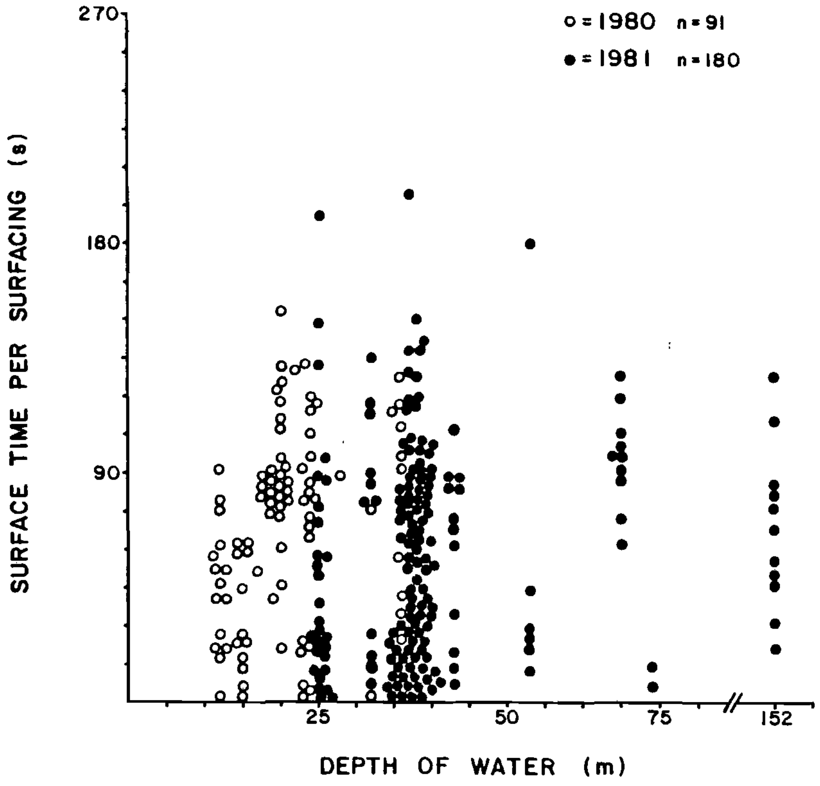


FIGURE 16.

Correlation of length of surfacing with depth of water, 1980 and 1981. There is a significant positive correlation in 1980 but not in 1981 or in both years combined.

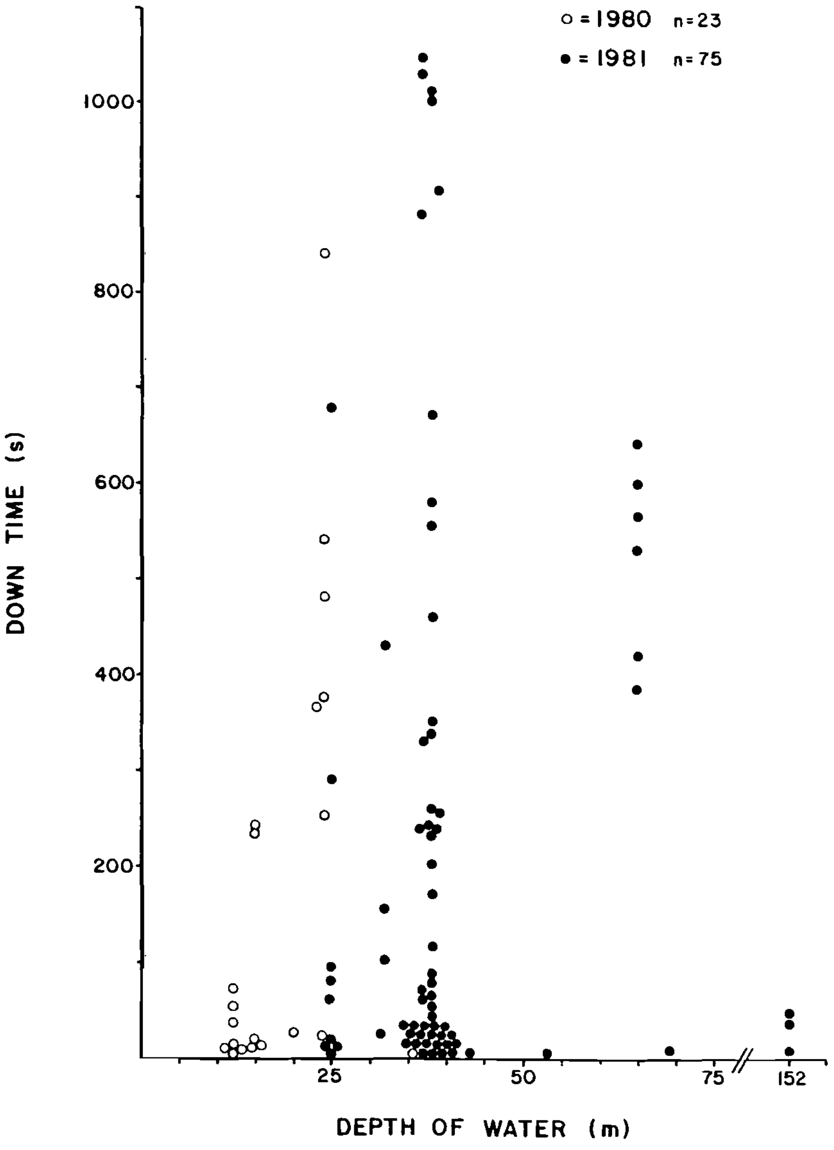


FIGURE 17.

Correlation of length of dive with depth of water, 1980 and 1981. The correlation is not significant for either year or for both years combined.

Effects of Time of Day

The interval between blows varied little with time of day, again demonstrating the relative stability of blow intervals (Fig. 18). Surface time and number of blows per surfacing were more variable, but did not display a consistent diel pattern (Figs. 19 and 20). The variability of these latter two variables is no doubt largely attributable to the particular behavior in which the whales were engaged, and not to the time of day (see below). The mean dive times were relatively uniform through the day (Fig. 21).

Dive Duration vs. Surfacing Characteristics

We looked at the relationship between the length of a dive and the characteristics of both the preceding and the subsequent surfacing. The length of dives was positively correlated with both the number of blows and the length of the subsequent surfacing ($r = 0.556$, df = 88, $p<0.001$; $r = 0.436$, df = 95, $p<0.001$; respectively). Length of dive was not significantly correlated with the value of either of these variables during the preceding surfacing, although the tendency was positive ($r = 0.190$, df = 68, $p>0.10$ for the previous number of blows; $r = 0.137$, df = 74, $p>0.10$ for the previous surface time). There was no indication that blow interval changed with the length of dive.

The mean dive time was considerably longer during fall migration in Baffin Bay (8.65 ± s.d. 2.73 min in 1979, n = 88) than in this study (3.17 ± s.d. 4.53 min, n = 115), but the surface time during that fall migration was only slightly longer (1.69 ± s.d. 1.01 min, n = 93) than our observations on the feeding grounds (1.09 ± s.d. 0.79 min, n = 319) (migration data from Koski and Davis 1980). Thus, whales overall spent about 25.6% of their time at the surface during summer in the eastern Beaufort, compared to about 16% during fall migration in the eastern Canadian arctic. As noted above, the 25.6% figure is somewhat biased owing to the probable tendency for longer dives to be underrepresented in our sample, and the actual figure is probably somewhat lower.

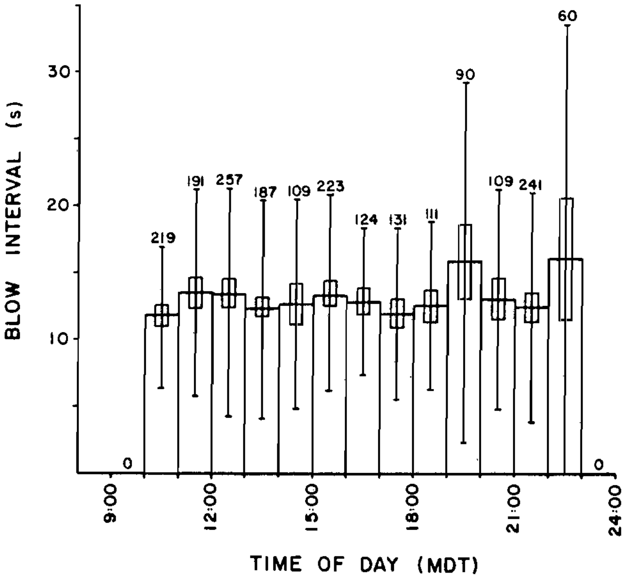


FIGURE 18. Mean interval between blows in relation to time of day, 1980 and 1981 airflight data combined. Presentation as in Figure 12.

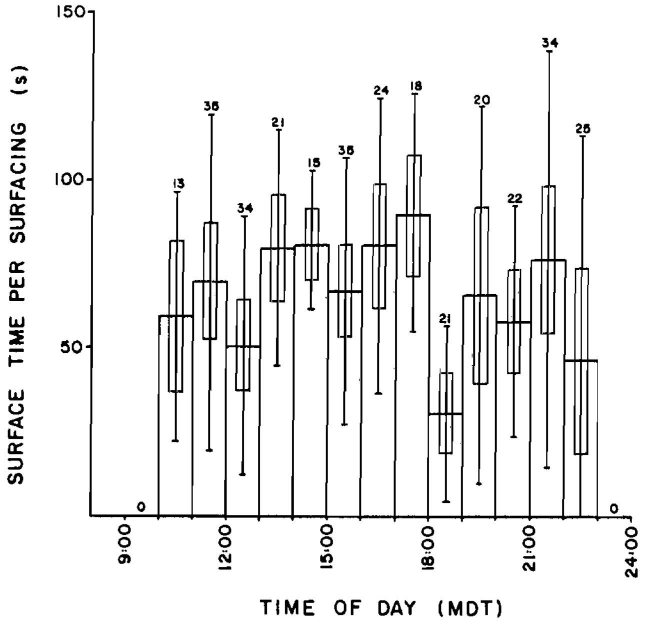


FIGURE 19. Mean surface time per surfacing in relation to time of day, 1980 and 1981 airflight data combined. Presentation as in Figure 12.

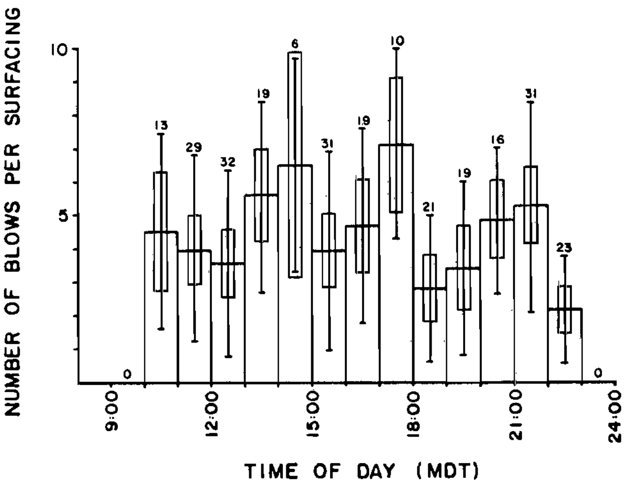


FIGURE 20. Mean number of blows per surfacing in relation to time of day, 1980 and 1981 airflight data combined. Presentation as in Figure 12.

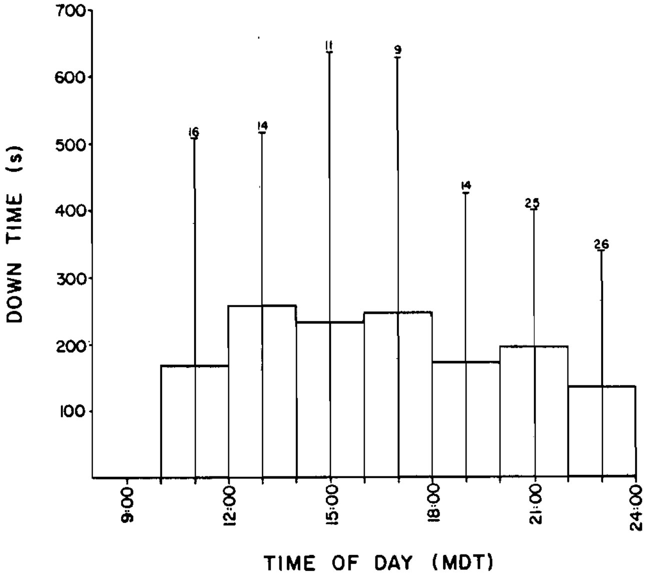


FIGURE 21. Mean down time in relation to time of day, 1980 and 1981 airflight data combined. Presentation as in Fig. 15.

The above results show that blow interval is less closely related to date, depth of water, hour of day, and duration of preceding dive than are the number of respirations per surfacing and the duration of surfacing. This appears to be so in other marine mammals as well. Dusky dolphins, for example, show remarkable differences in duration of dive and surface time on a diurnal and seasonal basis (Würsig 1976), but their respiration rate changes relatively little.

Effect of Status and General Activity

We have also examined the respiration and dive characteristics of five definable categories of whales: calves, adults with calves, socializing whales, skim feeders and water-column feeders. We will describe each in turn.

Calves and Mothers.--We saw adults with calves on six dates in 1980 and on five dates in 1981, and we collected quantitative data on nine of these dates (Fig. 22). The mean blow interval was longer in the maternal females than in other whales ($t = 4.10$, $df = 2004$, $p<0.001$), and the blow intervals of calves were comparable to those of other (non-maternal) adults. The longer blow intervals of the mothers suggest a lower activity level than that of the other whales. Recent work on mother-calf behavior in southern right whales found the mothers to be relatively inactive (Thomas and Taber in prep.). The surface time of calves (per surfacing) was significantly lower than that of adults without calves ($t = 2.37$, $df = 296$, $p<0.02$); this may be related to frequent dives below the mother in order to suckle. A correlated measure, the number of blows per surfacing, was also significantly lower for calves than for adults without calves ($t' = 5.46$, $df = 251$, $p<0.001$). There were no significant differences between the down times of the calves, the mothers, and the other whales (Kruskal Wallis test, $H = 1.614$, $df = 2$, $p>0.25$).

Carroll and Smithhisler (1980) present some complementary data for the spring migration period. At that time, as in summer, calves tend to surface for briefer periods than do other bowheads, and often blow only twice per surfacing. In contrast to our results, Carroll and Smithhisler found that calves and their mothers tend to dive for shorter periods than do other bowheads.

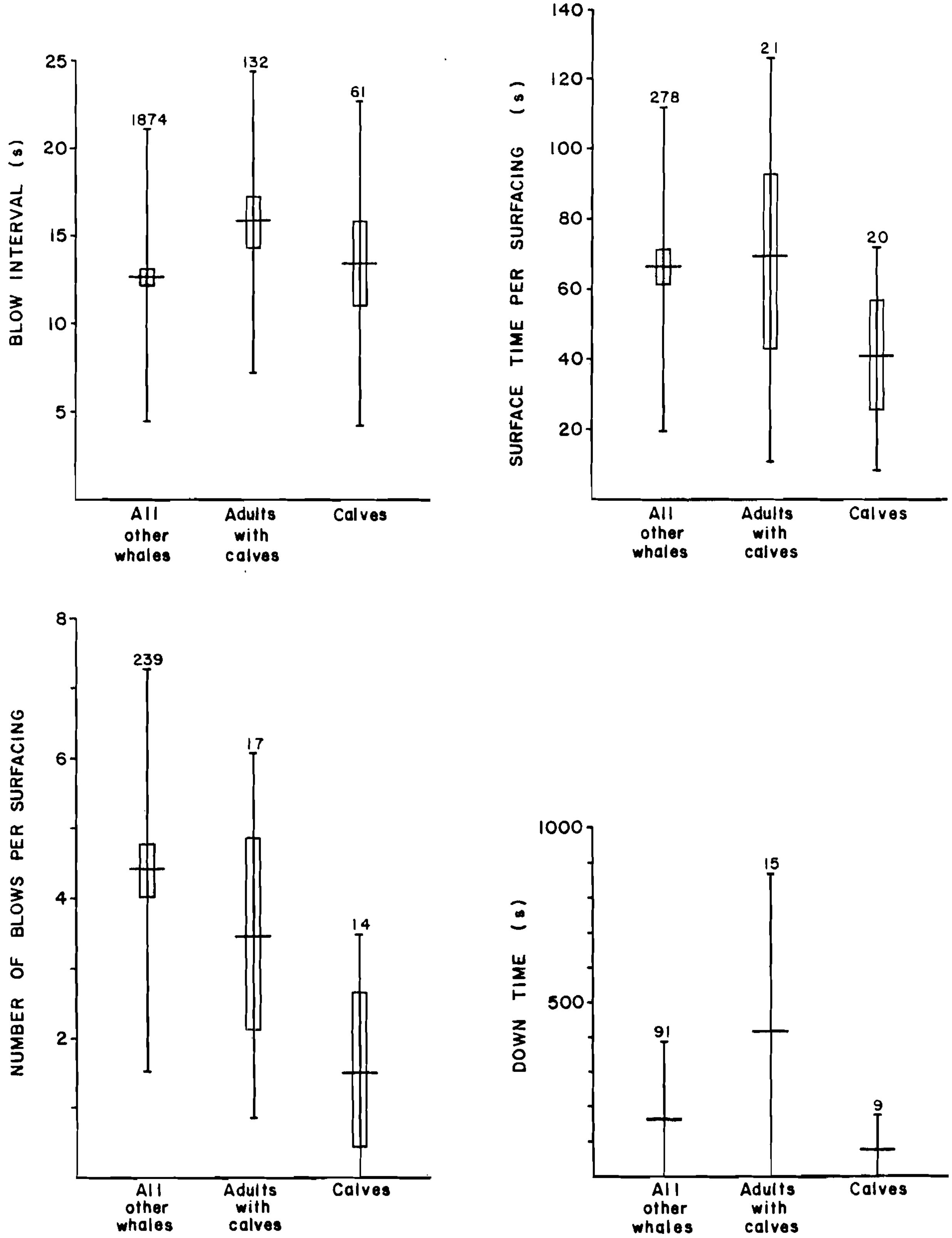


FIGURE 22. Comparison of surfacing characteristics and down times of calves, adults with calves, and all other whales. Presentation as in Figure 12.

Socializing vs. Non-Socializing Whales.--The surface times and number of blows per surfacing were not significantly different for socializing and non-socializing whales (Fig. 23). However, the blow intervals of socializing whales were significantly longer than those of non-socializing whales ($t' = 2.39$, df = 2065, $p<0.02$). Although the difference is statistically significant, the means differ by only 1.3 s (socializing mean = 14.0 ± s.d. 10.54 s, n = 426; non-socializing mean = 12.7 ± s.d. 7.44 s, n = 1641), and thus the blow intervals were not widely disparate. Nevertheless, those whales which interacted on a close basis with others were breathing less often than whales otherwise engaged. Since some of the non-social behavior consisted of water-column feeding, more rapid breaths during this feeding activity may be responsible for these results (see below).

Feeding and Non-Feeding Whales.--We compared whales that were skim feeding or classified as water-column feeding with non-feeding whales (all whales without any of the indications of feeding described above and without underwater blows). Skim-feeding whales (Fig. 24) had a mean blow interval marginally longer than the means for non-feeding and water-column feeding whales ($t' = 1.69$, df = 1785, $p<0.10$; and $t = 2.20$, df = 256, $p<0.05$, respectively). The mean blow interval for whales classified as water-column feeding was marginally shorter than that for non-feeding whales ($t' = 1.80$, df = 1877, $p<0.10$). The number of blows per surfacing and the surface time per surfacing varied in a consistent fashion for the three feeding categories. Whales that were water-column feeding blew more often and stayed at the surface longer than did non-feeding whales ($t = 3.82$, df = 238, $p<0.001$; $t = 2.87$, df = 284, $p<0.01$, respectively). Skim-feeding whales tended to blow less often and stay at the surface a somewhat shorter time than did other whales, but the differences are not statistically significant. We have no data on surfacing and respiration characteristics of undisturbed bottom-feeding whales.

Social Behavior

Behavior was termed social when whales were within one-half body length of one another or appeared to be pushing, nudging, chasing or obviously orienting their activities toward one another. Certainly animals very far apart could be interacting, and we assume that our observations of possible

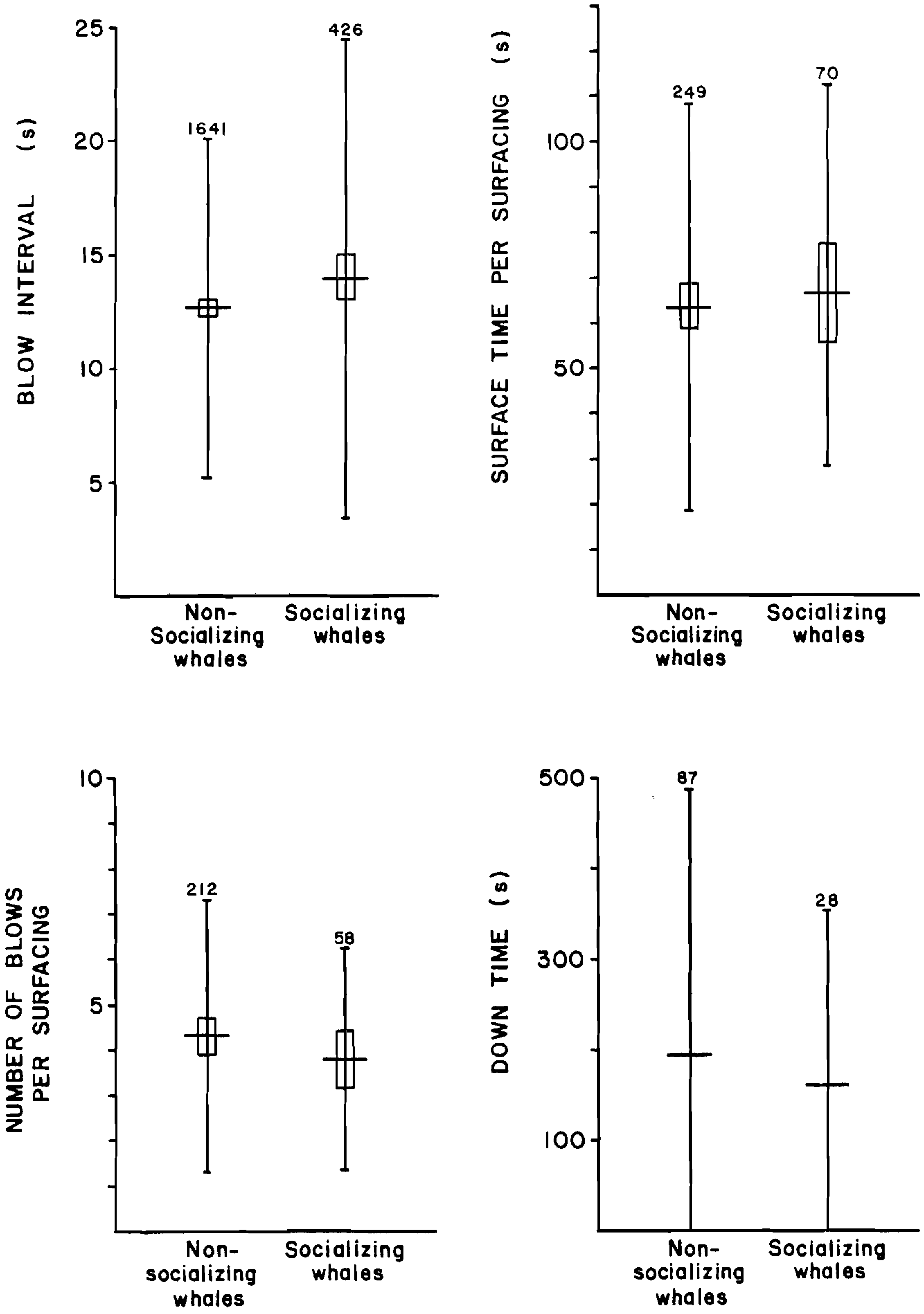


FIGURE 23. Comparison of surfacing characteristics and down times of socializing and non-socializing whales. Presentation as in Figure 12.

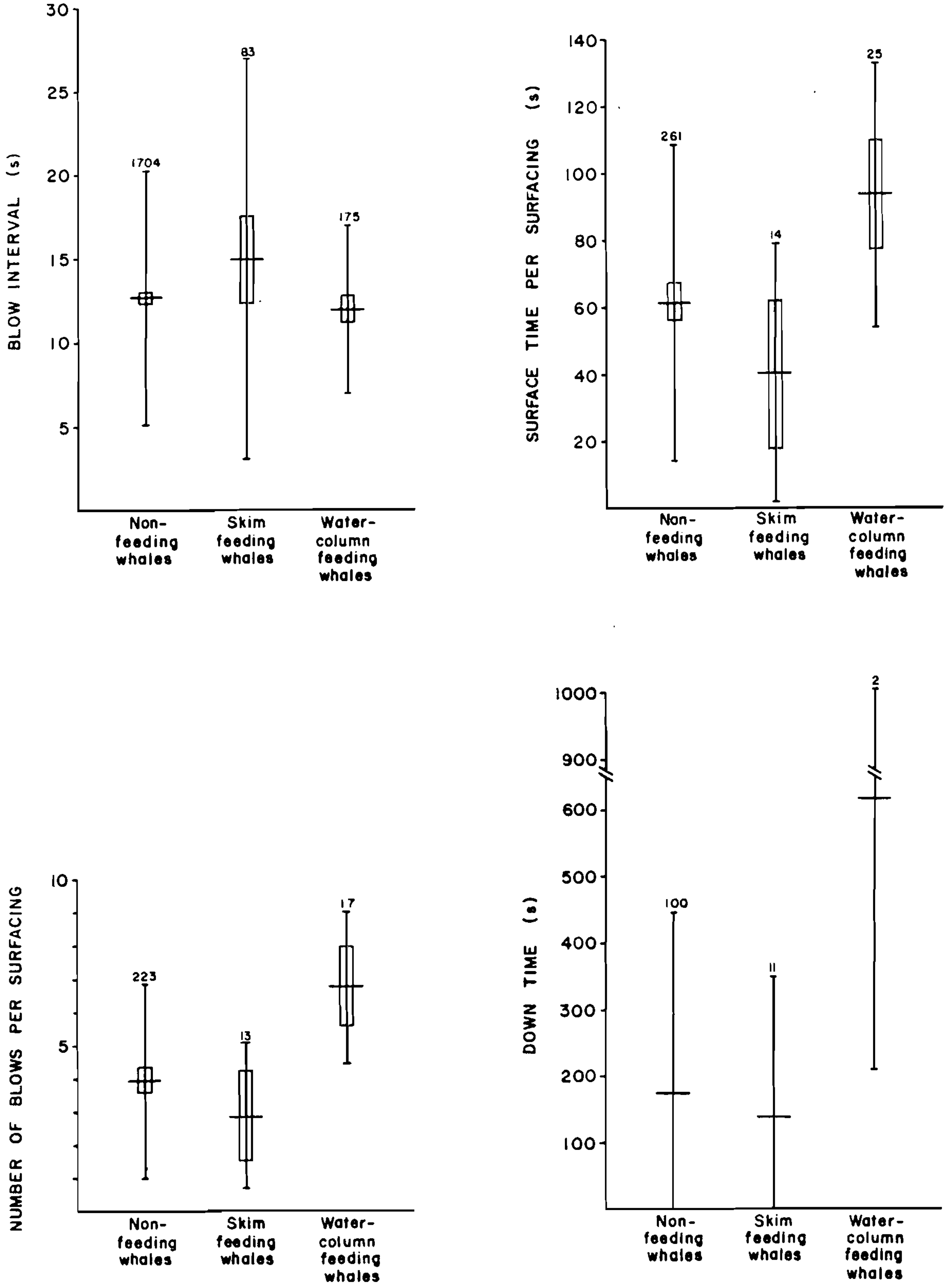


FIGURE 24. Comparison of surfacing characteristics and down times of skim feeding, water-column feeding and non-feeding whales. Presentation as in Figure 12.

synchronous dives over an area many kilometres in diameter represented a form of social interaction. However, only close interactions were unambiguously recognizable. Interactions between mothers and calves were not included as social interactions in this analysis. In 1980, we observed less social behavior than in 1981 and no apparent mating. In 1981 we observed mating or attempted mating at least twice. Because groups of whales usually could not be reidentified positively from one dive to the next, we treated observations of social behavior at intervals >5 min as independent for the purpose of counting number of interactions. Conversely, we did not score social behavior in the same area more than once in 5 min when counting its frequency.

Frequency of Socializing

Social behavior appeared to occur less frequently in late August-early September than in early August both in 1980 and 1981 (Fig. 25). In the first 10 days of August in 1980 and in 1981, we saw three or more social interactions per aerial observation hour during 5 of the 8 flights with data. This frequency of socializing was observed only once during the 17 flights with data after 10 August. Rugh and Cubbage (1980) and Carroll and Smithhisler (1980) report a higher incidence of social interactions during the spring migration around Alaska. The apparent waning of social activity that we observed as summer progressed may be part of a continuous decrease from the higher spring level.

There was some indication of hour-to-hour variation in amount of social activity (Fig. 26). There was a peak around 14:00-16:00 MDT, which is the noon period by sun time because MDT in the study area is about 3 h advanced relative to sun time. This peak was evident in both years. There was a possible secondary peak after 20:00. Why whales should engage in more social activity around noon (and possibly in the evening) than at other times is unknown, but diel rhythms are well known in several species of marine mammals (e.g., Saayman et al. 1973 for bottlenose dolphins; Matsushita 1955 for sperm whales; Schevill and Backus 1960 for humpback whales). It is possible that the increased level of socializing that we saw around noon is a reflection of a lowered level of feeding at that time, which Nemoto (1970) suggested for

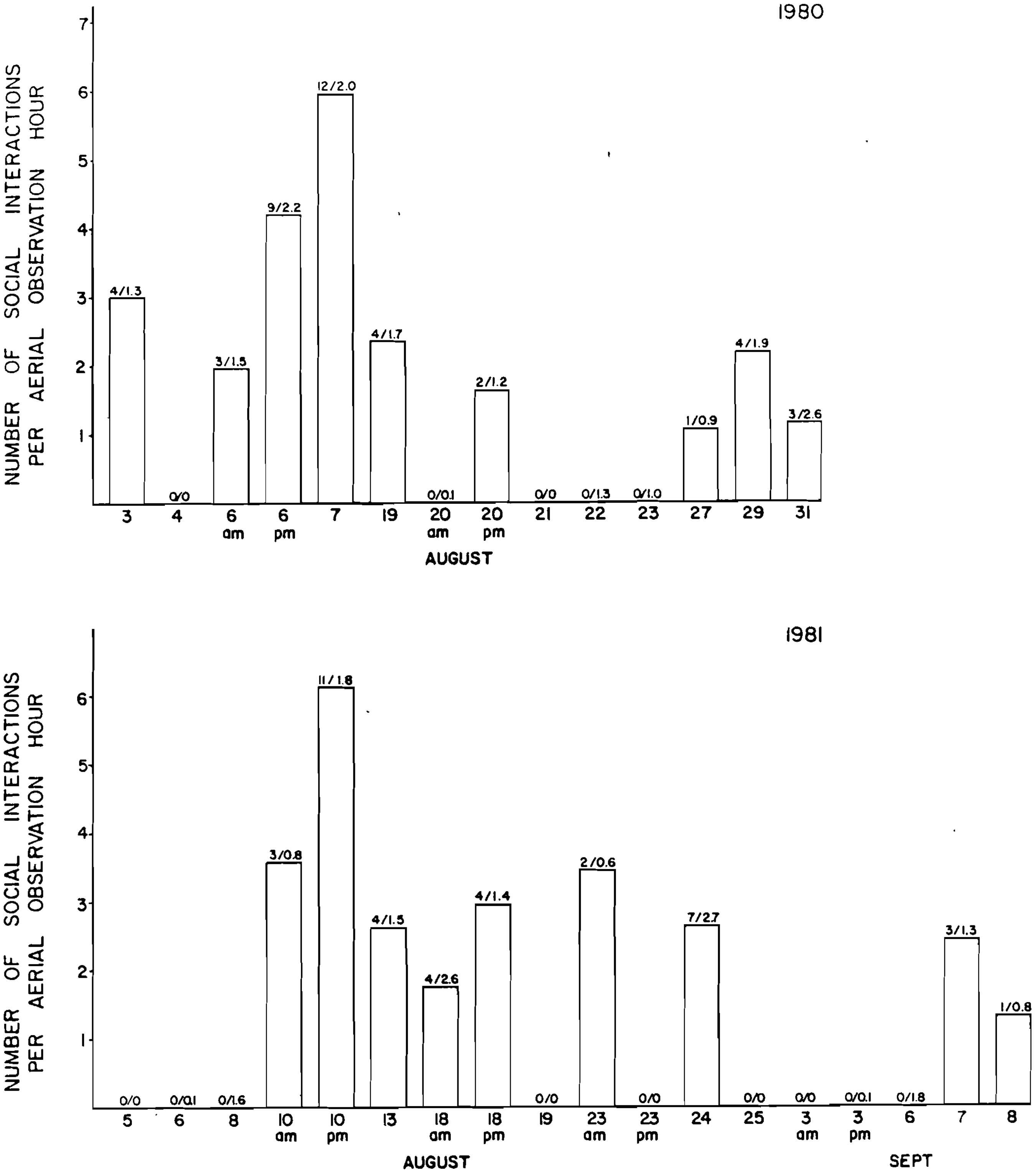


FIGURE 25. Number of observations of socializing per aerial observation hour during each airflight in 1980 and in 1981. The numbers at the top of each column are number of social interactions/number of observation hours.

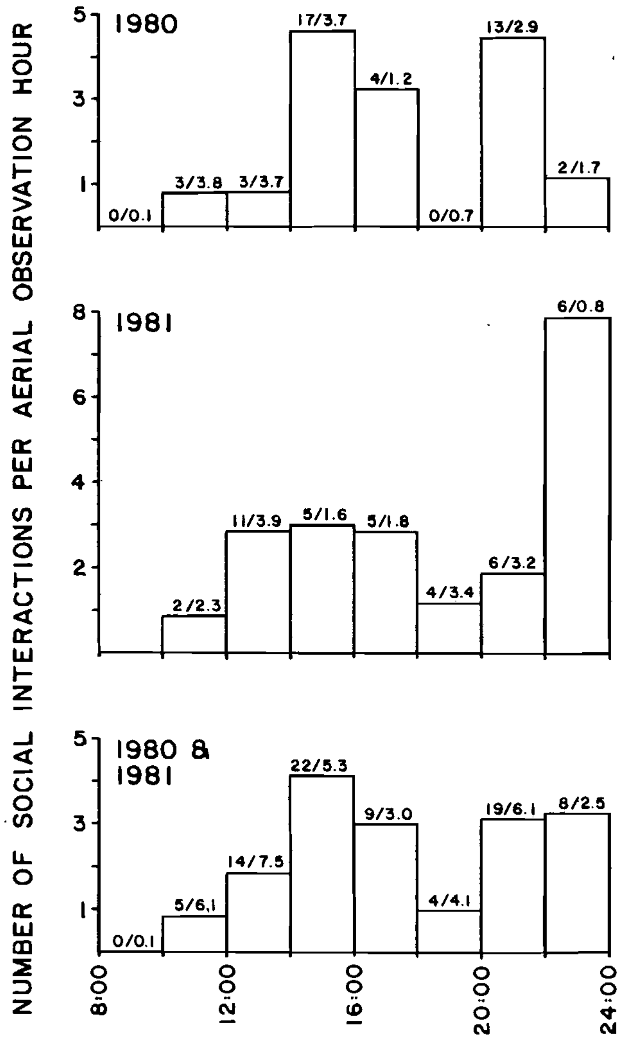


FIGURE 26. Number of observations of socializing per aerial observation hour in relation to time of day in 1980, 1981 and both years combined. Presentation as in Figure 25.

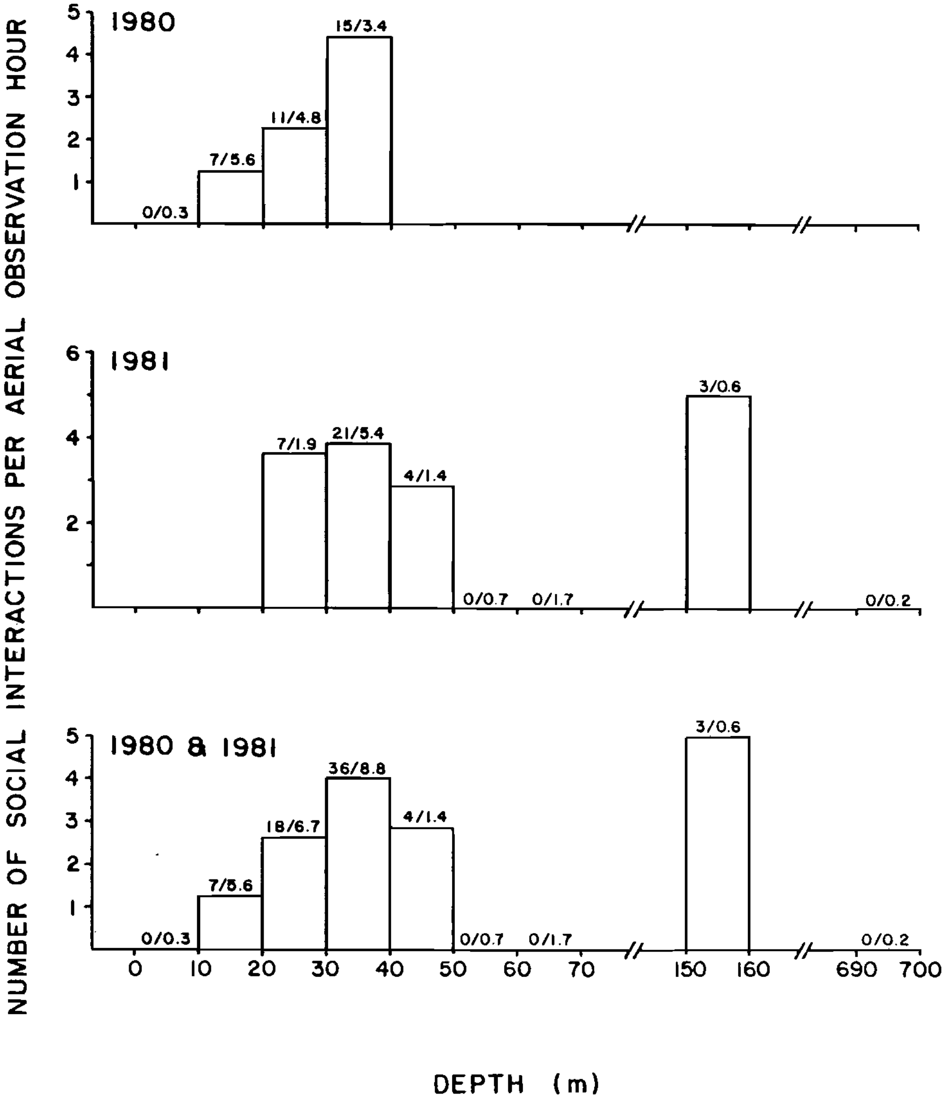


FIGURE 27. Number of observations of socializing per aerial observation hour in relation to depth of water in 1980, 1981, and both years combined. Presentation as in Figure 25.

baleen whales in general. The daily midday peak in socializing coincides with the daily minimum in underwater blowing (Fig. 6).

We found whales socializing in most of the water depths where whales were observed. There appeared to be a peak in rate of socializing between 30 m and 40 m (Fig. 27), but low sample sizes and inconsistencies between 1980 and 1981 preclude definite conclusions.

In the course of interacting with nearby whales, socializing whales often turn while at the surface. In contrast, non-socializing whales often come to the surface and dive again without changing direction. To compare this quantitatively, we calculated the incidence of turning for socializing and non-socializing whales:

	Socializing	Non-Socializing
Surfacings with turns	44	105
Surfacings without turns	77	324
Total surfacings	121	429
% surfacings with turns	36%	24%

The socializing whales made significantly more turns than the non-socializing whales (chi-square = 6.75, df = 1, $p<0.05$).

Group Structure and Stability

Two observations of recognizable bowheads provided some evidence about group structure and stability. We observed a distinctively marked pair of adults, one of which was accompanied by a calf, at about 70°10'N, 133°50'W, on 7 August 1980. One adult ('white tail') had a large amount of white along the trailing edge of its tail; the other ('triangle'), which was accompanied by a calf, had a large triangular white patch on the peduncle and adjacent part of the tail. We saw a similarly marked group of two adults and a calf, almost certainly the same whales, on 20 August at 70°07'N, 131°30'W, which is about 100 km from the place they had been seen two weeks earlier. This observation suggests that bowheads sometimes have some sort of stable group structure that is maintained for at least a few weeks. The observation also suggests that females with calves may sometimes be accompanied by escorts, as has been observed for humpback whales (Herman and Antinoja 1977).

Apparent Mating Activity

In 1981, we observed apparent mating activity on two occasions. The most prolonged observation of apparent copulatory behavior was on 10 August 1981 about 70 km northwest of Pullen Island. This observation was made within a 25 km^2 area where there were 20-30 whales whose main activity was socializing. Two whales interacted for over one hour, with chases, flipper caresses, belly to belly orientation, rolls toward and away from each other, head nudges to the genital area and to the rest of the body, tailslaps, and flipper slaps. This activity was videotaped. It appeared that one of the whales, a recognizable animal that we termed 'Whitespot', was about 1-2 m longer than the other whale ('B') and was the more aggressive. Although B originally nudged the genital area of Whitespot, it was Whitespot who appeared to initiate flipper caressing and rolls toward B. The two whales rolled their ventrums together for about 5 s, but B then rolled its ventrum in the air in an apparent attempt to avoid ventral contact with the larger animal. As it rolled away from Whitespot, B defecated, and when Whitespot moved its head toward the genital area of B, B defecated two more times in rapid succession. B then dove away from Whitespot, and Whitespot followed it at the surface in an apparent chase. Whitespot then stopped and, alone at the surface, rolled two times and tail slapped while on its back. It then dove, and the two appeared together again at the surface 4 min later, with no further energetic surface interactions.

Unfortunately we do not know the sex of either animal, but the observers had the strong impression that Whitespot was attempting to copulate with the reluctant animal. Some of us (BW, CC, RP) have observed southern right whale females frequently roll their ventrums away from aggressive males, leaving their genital areas above the surface of the water where the males cannot reach them. Our observations here were highly reminiscent of such behavior, and although adult females are slightly larger than adult males in both right and bowhead whales, we commonly see large southern right whale males in pursuit of smaller females which attempt to avoid them.

On 25 August 1981, approximately 28 km northwest of Pullen Island, we observed a recognizable whale ('Tan') in 10-13 m water depth opening and closing its mouth at the surface, and emitting clouds of mud from its mouth. We suspect that it had been feeding near the bottom in the relatively shallow water, and was cleaning its baleen at the surface. Other whales in the vicinity, 15 or more body lengths from Tan, emitted similar clouds of mud after surfacing. Approximately 1/2 h after this apparent feeding, Tan was joined by another whale, and the two rolled their ventrums together, while clasping each other with their flippers. This lasted for 1 min; then they rolled apart simultaneously, blew, and dove slowly as a third whale approached. The mutual rolling and leisurely diving behavior of this pair indicated that, if this was copulatory behavior, it was mutually undertaken by the two whales, in contrast to the previous example.

Apparent sexual activity during spring migration around Alaska has been described by Everitt and Krogman (1979), Carroll and Smithhisler (1980), Rugh and Cubbage (1980), Johnson et al. (1981) and Ljungblad (1981). Although the eastern Beaufort Sea has traditionally been regarded as part of the feeding grounds for the bowheads, we have found socializing to be an important component of their behavior there during summer, perhaps with occasional mating. The frequency of this activity may fluctuate from year to year, but both feeding and socializing occur in both the eastern Beaufort Sea in summer and the Alaskan Beaufort Sea during one or both migration periods.

Bowhead Sounds

There are few reports documenting the types of sounds produced by bowhead whales. Poulter's reports (1968, 1971) on purported bowhead sounds probably describe bearded seal songs. It is only in the last several years that there have been reliable documentations of bowhead sounds (Braham et al. 1979, 1980b,c; Ljungblad et al. 1980a, 1982; Clark and Johnson in prep.). These studies have all been during migration (spring and fall) or during late winter, and all have been in Alaskan waters. In general, most of the sounds have been described as moans, although pulsive growls, screams and roars have also been recorded. All reports have concentrated on descriptions of the sounds and have not attempted to correlate sounds with behaviors. Thus, although we are beginning to document the types of sounds these whales produce, we have no clear understanding of the biological significance of the various sound types.

Intensity levels for bowhead sounds have been estimated to be in the range of 135 to 145 dB re 1 µPa at 100 m (Clark and Johnson in prep.). These levels translate to source levels of about 175 to 185 dB re 1 µPa at 1 m, which are similar to source levels estimated for the blue whale (188 dB, Cummings and Thompson 1971) and fin whale (180 dB, Payne and Webb 1971) and measured for the closely related southern right whale (181-186 dB, Clark unpubl.).

In this section we describe types of bowhead sounds recorded via sonobuoys deployed in the eastern Beaufort Sea during the summers of 1980 and 1981. The hydrophone was usually deployed to 18 m or the bottom, whichever was less. These sounds are compared to those recorded in May of 1979 and 1980 off Point Barrow (Clark and Johnson in prep.). Some attempt will be made to place the sounds in a functional perspective by comparing them to the calls of southern right whales (Payne and Payne 1971; Cummings et al. 1972; Clark 1982a,b).

All sounds were listened to at normal speed, and a general description of each sound, its relative intensity, and time of occurrence were noted. Sounds judged to be of sufficient intensity to permit analysis were converted into hard copy spectrograms using a Spectral Dynamics (SD 301C) real-time analyzer or a Kay 6019A Spectrograph. From the spectrograms we measured the sound's initial, final, lowest and highest frequencies (± 10 Hz), and its duration (± 0.1 s). The types of sounds were determined by visual inspection of the spectrograms, or from the aural impression of the sound, or both. Because of the frequency response characteristics of the sonobuoys (Greene 1982: Fig. 2), high frequencies are somewhat overemphasized in the spectrograms. However, this does not affect the analyses reported here.

Table 5 lists the dates and times during which bowhead sounds were recorded in 1980 and 1981. Next to each date is a listing of any industrial noise (seismic impulses, ship noise, etc.), the approximate number of whales within a 3-4 km radius of the sonobuoy, the general behavior of the animals, the rate of call production in calls per whale-hour, and a tabulation of the

Table 5. Daily summary of various types of bowhead sounds recorded in 1980 and 1981.

						# Sounds of Each Type								
						calls							Other	
Date	Observation Time (MDT)	Industrial noise	# animals	Behavior	Call rate (calls/whale-h)	up	down	const.	double or inflected	high	harmonic	pulsive	blows	slaps
7 Aug 1980	1432-1501	none	7	mild social	9.1	8	2	1	0	0	20	0	1	0
22 Aug 1980	1333-1420	none	12-15	skim feeding	1.0	4	5	1	1	0	0	0	56	0
22 Aug 1980	*1935-2035	seismic	7	no observations	5.6	17	6	1	3	9	3	31	0	0
23 Aug 1980	1058-1145	none	5	skim feeding	2.6	6	1	0	0	0	3	0	36	0
27 Aug 1980	*1919-2230	ship disturbance	?	no observations	?	3	1	1	0	1	0	11	0	0
29 Aug 1980	1316-1442	none	8-10	mild social	1.3	2	3	0	8	0	1	0	8	0
5 Aug 1981	0956-1029	none	5	swimming	30.5	25	7	10	8	10	2	22	4	0
5 Aug 1981	*1029-1041	seismic	5	swimming	13.0	5	0	0	0	2	0	6	2	0
10 Aug 1981	1304-1359	none	2	resting	0.0	0	0	0	0	0	0	0	0	0
10 Aug 1981	1439-1424	none	5	mild social	1.1	0	0	0	0	1	0	3	0	0
18 Aug 1981	1030-1332	none	10	swimming	1.4	24	5	1	1	3	3	5	2	4
18 Aug 1981	1821-1949	faint ship noise	20-30	feeding	0.3-0.4	4	3	0	0	0	1	3	43	0
18 Aug 1981	*1949-2009	airgun	20-30	feeding	0.0	0	0	0	0	0	0	0	0	0
18 Aug 1981	2009-2215	faint ship noise	20-30	feeding	0.9-1.3	33	3	1	1	5	12	2	83	0
19 Aug 1981	*1259-1346	ship disturbance	5-6	feeding	0.0	0	0	0	0	0	0	0	9	1
19 Aug 1981	*1346-1426	ship disturbance	5-6	mild social	1.0-1.2	3	0	0	1	0	0	0	2	0
19 Aug 1981	*1426-1445	airgun	5-6	mild social	0.5	1	0	0	0	0	0	0	0	0
19 Aug 1981	1445-1533	faint seismic	4	mild social	0.3	1	0	0	0	0	0	0	2	2
23 Aug 1981	1109-1156	faint seismic	5-6	mild social	2.1-2.6	5	3	1	0	1	0	0	2	0
23 Aug 1981	1826-2125[a]	ship noise briefly and faint seismic	12	active social	10.1	68	19	7	6	46	114	103	31	6
23 Aug 1981	*1951-2125[b]	ship noise	12	active social	0.0	0	0	0	0	0	0	0	0	0
24 Aug 1981	*1439-1535	ship noise and seismic	12	swimming	0.9	3	4	0	0	1	0	2	0	0
25 Aug 1981	*1125-1224	seismic	15	swimming	0.5	7	0	0	0	0	0	0	1	0
25 Aug 1981	*1224-1238	seismic	4	mild social	4.2	4	0	0	0	0	0	0	1	0
25 Aug 1981	*1240-1250	ship noise and seismic	1 3	log playing mild social	1.5	1	0	0	0	0	0	0	1	0
25 Aug 1981	*1250-1435	seismic	4-6	swimming	3.0-4.4	17	7	0	0	1	5	1	0	0
3 Sep 1981	*1152-1321	airplane disturbance	6	no observ.	1.1	9	0	0	0	1	0	0	0	0
3 Sep 1981	1853-1914	none	5	no observ.	0.0									
8 Sep 1981	2129-2233	none	6	active social	22.4	10	3	1	0	27	10	70	5	4

* Potentially disturbed condition.

[a] and [b] represent two sonobuoys deployed and monitored simultaneously.

number and types of sounds recorded. Call rate was computed by dividing the number of calls by the duration of the observed behaviors (see 'Time' column, Table 5) and by the number of whales involved. Blows and slaps are excluded from the call rate.

Blow and Slap Sounds

The data in Table 5 reveal a striking difference between the number of blow sounds heard from feeding whales and whales engaged in other behaviors. Feeding whales produced between 1.0 and 9.2 blow sounds per whale-hour compared with 0.0 to 1.4 blow sounds per whale-hour for any other behaviors. If blow sounds on 18 August 1981 are assumed to have been detected only from the 10 whales that were within approximately 2 km of the hydrophones, then the minimum blow sound rate for feeding whales was 2.5 instead of 1.0. This difference in blow sound rates between whales engaged in feeding and other behaviors does not appear to be attributable to a difference in respiration rates or to greater distances between the hydrophones and the non-feeding groups; blow rates and distances from the sonobuoys were generally the same on all 14 days of recording. There are several other possible explanations for these differences in the number of audible blow sounds. Relative to the non-feeding whales, feeding whales might have been blowing more forcefully and/or they might have had their nostrils closer to the air-water interface when blowing. However, in our oblique-angle video recordings made from the air, feeding whales do not appear to be blowing more forcefully (as judged by the height of the blow), and observers did not note any differences between the exhalations of feeding and non-feeding whales. There is evidence from the behavioral observations that feeding whales blew while underwater more often than did the non-feeding animals. Although we have no good explanation for the difference between the number of blow sounds heard from feeding as opposed to non-feeding animals, we wonder whether the louder blows may help to synchronize surfacings of whales and may explain the possible synchrony in surfacings discussed above.

Bowhead slap sounds, which are best described as short (<0.2 s), broadband (0-1 kHz) signals with sharp onsets, were difficult to identify because of their similarity to certain ship noises. In Table 5 slap sounds are tallied only if they were loud and relatively undistorted, and occurred when nearby ships were quiet. These counts are probably underestimates of the actual number of slap sounds produced by the whales.

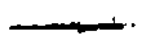
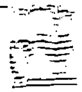
Call Types and Their Characteristics

Table 6 gives the means and standard deviations of several acoustic parameters for each of the eight call types that were recognized. Table 6A includes sounds recorded during both undisturbed and potentially disturbed conditions, while Table 6B includes only sounds recorded during undisturbed conditions. This tabulation includes only those sounds that were of sufficient quality for reliable measurements. In the remainder of this section, sounds that were not blow sounds or slap sounds will be referred to as calls.

Not including blow sounds and slap sounds, the majority of sounds (57%) were tonal, frequency modulated (FM) calls lasting 1-2 s (see Fig. 28). These tonal calls were usually a single note that was ascending (Fig. 28A,B), descending (Fig. 28D), or constant (Fig. 28C) in frequency. Most FM calls contained acoustic energy between 100 and 250 Hz (see Table 6) but there were some relatively high FM calls (Fig. 28I) with frequencies between 400 and 1200 Hz. Occasionally FM calls were inflected (Fig. 28F), composed of two notes (Fig. 28E), or lasted up to 3 s (Fig. 28G). These rarer types of calls were typically restricted to frequencies below 400 Hz, although a few inflected calls and long calls were above 400 Hz.

Another FM call type was characterized by its rich harmonic spectrum (Fig. 28H) which gave the call the aural quality of sounding like a 'purr'. Fundamental frequencies were between 30 and 110 Hz. In any one sound the fundamental remained relatively constant, never varying by more than 30 Hz. These sounds contained as many as 16 harmonics, with the harmonic bands being integral multiples of the fundamental. Detailed oscillographic analysis of these calls revealed that they were not pulsatile (see Broughton 1963; Watkins 1967). This evidence strongly suggests that the multiple harmonic spectrum is generated at the anatomical sound source (see Greenewalt 1968) and is not the result of spectral shaping by resonance cavities.

Table 6. Acoustic parameters of bowhead call types during (A) all conditions and (B) presumably undisturbed conditions, 1980-1981. Mean ± s.d. are shown.

	Call Type							
Acoustic Parameter	 up	 down	 constant	 inflected	 double	 high	 harmonic	 pulsive
A. ALL CONDITIONS								
Initial frequency (Hz)	137 ± 55	184 ± 52	225 ± 24	243 ± 48	210 ± 45	720 ± 295	68 ± 16	———
Final frequency (Hz)	173 ± 71	130 ± 38	228 ± 24	240 ± 25	250 ± 115	666 ± 216	66 ± 16	———
Lowest frequency (Hz)	137 ± 55	184 ± 52	225 ± 24	157 ± 48	146 ± 50	590 ± 160	———	1026 ± 385
Highest frequency (Hz)	173 ± 71	130 ± 38	225 ± 24	242 ± 45	256 ± 82	793 ± 182	———	1536 ± 408
Duration (s)	1.3 ± 0.5	1.3 ± 0.4	1.1 ± 0.4	1.3 ± 0.5	2.1 ± 0.2	0.7 ± 0.3	1.4 ± 0.4	1.3 ± 0.6
Sample size	96	31	20	17	9	15	50	62
B. UNDISTURBED CONDITIONS								
Initial frequency (Hz)	141 ± 56	184 ± 52	225 ± 24	243 ± 48	210 ± 45	720 ± 295	68 ± 16	———
Final frequency (Hz)	169 ± 73	130 ± 38	228 ± 24	240 ± 25	250 ± 115	666 ± 216	65 ± 16	———
Lowest frequency (Hz)	141 ± 56	184 ± 52	225 ± 24	157 ± 48	146 ± 50	590 ± 160	———	1022 ± 387
Highest frequency (Hz)	169 ± 73	130 ± 38	225 ± 24	242 ± 45	256 ± 82	793 ± 182	———	1536 ± 408
Duration (s)	1.3 ± 0.5	1.3 ± 0.4	1.1 ± 0.4	1.3 ± 0.5	2.1 ± 0.2	0.7 ± 0.3	1.4 ± 0.4	1.3 ± 0.6
Sample size	86	30	20	16	9	15	48	59

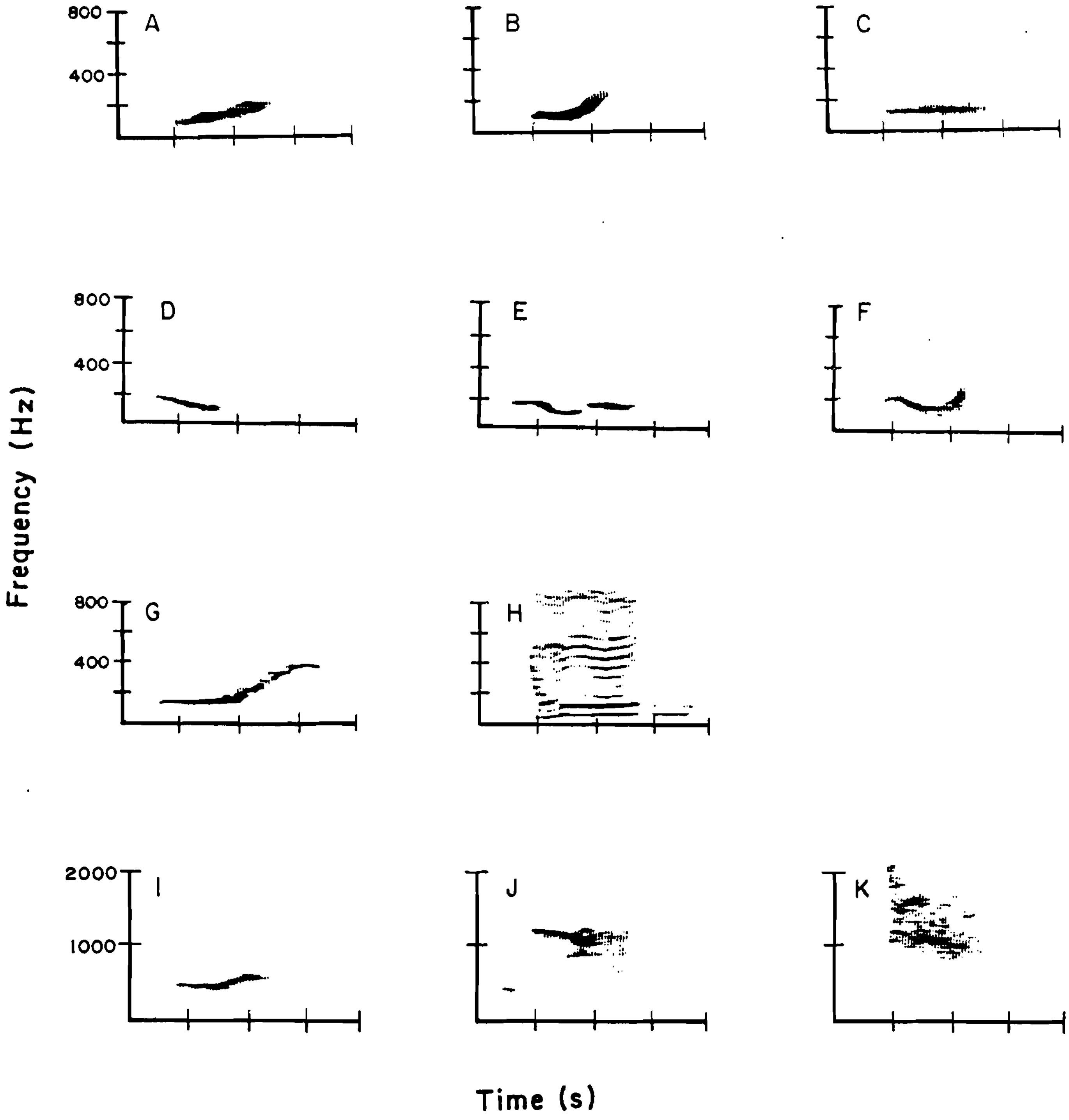


FIGURE 28. Representative bowhead sounds: (A and B) ascending calls, (C) constant call, (D) descending call, (E) two-note call, (F) inflected call, (G) long call, (H) harmonically rich call, (I) high call, (J) hybrid call, and (K) pulsive call. Each division on the time axis represents 1.0 second. Note that the frequency scale in I-K (0-2000 Hz) differs from that in A-H (0-800 Hz).

The last major call type was a complex pulsive sound containing broadband energy principally in the 400 to 2000 Hz band (Fig. 28K). The pulsive and broadband characteristics of these calls gave them the aural quality of sounding like a 'screech' or high pitched 'roar'. These complex pulsive calls have been heard in Alaskan waters, where they have sometimes been referred to as 'elephant-like roars' (Ljungblad et al. 1982). Pulsive calls were often produced in a series with as many as 15 calls heard in 27 s.

Three calls were recorded that were intermediate between a tonal FM call and a pulsive call (Fig. 28J). All three of these hybrid type calls began as a high (>400 Hz) sound and ended as a broadband pulsive sound.

Context of Call Types

From the data tabulated in Table 5 there is some indication that the types and numbers of calls produced are correlated with the types of behaviors observed. At this point, sample sizes are too small to test for the significance of these possible correlations, but general associations are becoming apparent with increasing amounts of observation time. It should be recognized that the call rate data are somewhat confounded by the fact that it was not known which whales in the area were responsible for the sounds. This potential problem was minimized by considering only five types of behaviors: resting, swimming, feeding, mild socializing and active socializing. These categories are not necessarily mutually exclusive. However, one can consider them to be graded from low levels of physical activity (resting) to high levels of physical exertion (active socializing).

On days when whales were either resting, swimming, feeding or mildly socializing, the rates of calling (see Table 5) usually were relatively low, while on the two days when whales were actively socializing, calling rates were high. The elevated calling rates during both days with active socializing are mostly attributable to the great number of high calls and pulsive calls on those dates. A few high calls were produced on other days but never to the extent that they were during active socializing. A few pulsive calls were also heard on three occasions when whales were swimming and there was concurrent seismic activity, and on five other days when whales were swimming, feeding or mildly socializing but there was no seismic activity.

The extent to which seismic activity and/or ship noise affects sound production is difficult to assess with these data because of the limited number of observations and the fact that almost all sound recordings contained some amount of industrial noise. In Table 7, the total numbers and the average rates of sounds produced during the five different behaviors are given depending on whether the observation was considered 'presumably undisturbed' or 'potentially disturbed'. For those behaviors where observations were made under both conditions, the average rates of sound production were always higher during undisturbed conditions than during disturbed conditions. This trend suggests that increases in local ambient noise conditions due to industrial activity affect the rate at which whales produce sounds. There does not appear to be any effect on the characteristics of the sound types (see Table 6), but the number of sounds that were measured for acoustic parameters under disturbance conditions was very small (n = 17). For additional discussion of call rates in the presence of industrial noise, see the 'Disturbance' section (Fraker et al. 1982).

All of the types of sounds recorded during the present project have also been recorded during spring migration past Point Barrow (Ljungblad et al. 1982; Clark and Johnson in prep.). Only a few high frequency FM calls and complex pulsive calls were heard in August 1980 when only 3.5 h of recordings were made and there were no observations of active socializing. Many more of these two call types were subsequently recorded in August and September 1981, when 23 h of recordings were made and active socializing was observed. Because our limited summer recordings include all the call types that have been recorded during the more extensive spring work, it is possible that the entire call repertoire of the bowhead has now been documented during both the spring and summer seasons.

There were differences between the spring and summer seasons in the relative numbers and rates of the various calls. In spring 1980, 81% of the calls were low, tonal FM sounds, 12% were harmonically rich calls, and the remaining 7% were high FM and pulsive calls. Of the low, FM calls, 32% were ascending in frequency while 46% were descending. In summer 1981, 41% of the

Table 7. Summary of numbers and rates of bowhead sounds during presumably undisturbed and potentially disturbed conditions; * = potentially disturbed conditions (does not include 23 August 1981, times 1951-2125, observation).

Behavioral Activity	No. groups	Call rate (calls/whale-h)	# hours	# whale-h	up	down	constant	double	inflected and high	harmonic	pulsive
Resting	1	0	0.92	1.8	0	0	0	0	0	0	0
*Resting	0	-	0	-	-	-	-	-	-	-	-
Swimming	2	3.8	3.58	33.1	49	12	11	9	13	5	27
*Swimming	4	1.7	3.87	35.7	32	11	0	0	4	5	9
Feeding	4	1.1	5.12	85.0	47	6	2	2	5	16	5
*Feeding	2	0	1.10	10.3	0	0	0	0	0	0	0
Mild Socializing	5	2.3	4.25	25.8	16	8	2	8	2	21	3
*Mild Socializing	4	1.5	1.38	6.5	9	0	0	1	0	0	0
Active Socializing	2	16.0	3.05	30.2	78	22	8	6	73	124	173
*Active Socializing	0	-	0	-	-	-	-	-	-	-	-

calls were low FM sounds, 18% were harmonically rich calls, and 41% were high FM and pulsive calls. Of the low FM calls, 69% were ascending in frequency and only 17% were descending. Call rates for ascending low FM calls were similar for both seasons, but rates for low FM downsweeps were about 5.0 calls per whale-hour in spring but only 0.5 calls per whale-hour in summer.

Although we have no direct behavioral evidence by which to assign communicative functions to the sounds of bowheads, we can infer some general functions from the data gathered so far and by referring to what is now known of southern right whale calls (Clark 1982a,b).

Clark demonstrated that the up calls (tonal, FM upsweeps) of right whales are contact calls. Single animals were most likely to produce these sounds, and two single swimming animals were often observed calling back and forth before joining. The low frequency upsweeps from bowheads are essentially identical to the up calls of southern right whales, and it seems possible that these similar signals serve a similar function as contact calls.

Clark (1982a) also suggested that, in right whales, the low FM downsweeps are a form of contact call that helps to keep whales in acoustic range but do not bring them into physical contact. These calls may have a similar function for the bowhead. Production rates for descending calls in the spring are an order of magnitude greater than rates in the summer. If one assumes that, during spring migration through largely ice-covered waters, it is important for the whales to remain in contact as an 'acoustic herd', then one would expect them to produce contact sounds. The descending call is the predominant sound during migration and it is produced at unusually high rates.

On both occasions when bowheads were socially active, high FM and complex pulsive calls were heard. Although a few of these call types were also recorded under different behavioral circumstances, it was only when the whales were active that the majority of calls were of these types. These results are very similar to those documented for southern right whales (Clark 1982a,b). Clark found that socially active (including sexually active) right whales almost always produced a series of sounds that were either high FM, hybrid or pulsive calls. Clark concluded that high calls were indicative of excitement and that pulsive calls were aggressive sounds used in agonistic contexts. The fact that socializing bowheads were heard making similar sounds suggests that the active social groups contained both males and females, and that high FM and pulsive sound types have a similar function for the bowhead.

In summary, the sounds recorded from bowheads in the eastern Beaufort Sea during August 1980 and August and September 1981 were similar to those recorded from animals off Point Barrow, Alaska, during their spring migration. It is possible that the full repertoire of call types has now been recorded during the summer season. Differences between seasons were found in the relative proportions and rates of the call types, but no qualitative differences were evident. The most obvious seasonal differences were in the production rates for descending calls; these calls were about 10 times more frequent in spring than in summer. Conversely, more high calls and pulsive calls were recorded in summer. There was some association between sound types and the behaviors of the whales. In general, resting, swimming, feeding and mildly social animals had low rates of sound production and made mostly low FM calls, while active socializing whales had high rates of sound production and produced mostly high FM calls and complex pulsive calls. From a comparison with the southern right whale, it appears that the bowhead and right whale have similar acoustic repertoires and that many of their sounds may have similar communicative functions.

Shore Observations

During late summer of 1980, bowhead whales usually stayed at least 5 to 15 km from the east end of Herschel Island (69°35'N, 138°51'W). In late summer 1981, whales were seen somewhat closer to the island, from 2 to 10 km away. Because of the large distances involved in both years, behavioral data obtained from shore were restricted to the most conspicuous attributes. Breaching and other forms of aerial behavior were especially well documented in 1981.

Water Depth

We determined the positions of whales and calculated the water depth over which the whales travelled. There is a bias for shallow water in these data because we could only determine the position of whales while they were within sight of the observation point. However, the bias is consistent, so we can look for variations within the data from day to day and from hour to hour.

From 3 to 12 September 1980, most whales were in approximately 32 m of water, and the mean depth did not change appreciably throughout the day (mean = 32.0 ± s.d. 10.24 m, n = 179, Figure 29). However, during the evening the variance in water depths at locations where whales were sighted appeared to increase. Thus, in the morning the bowheads strongly favored waters slightly over 30 m deep, while later in the day they appeared to spread to shallower and deeper water. From 29 August to 10 September 1981, whales were in an average of about 36 m of water (mean = 36.3 ± s.d. 9.36 m, n = 78). This mean depth did not change appreciably on an hourly basis, and there was no indication of greater variance in depths during the evening.

Surfacing Characteristics

Because we were not able to identify particular whales from one dive to the next, and we often did not observe them for complete surfacings, the only data on surfacing characteristics that we could obtain were on blow intervals. The mean blow interval of undisturbed whales observed from shore was 13.6 ± s.d. 8.44 s (n = 24) in 1980 and 15.3 ± s.d. 10.31 s (n = 36) in 1981. The overall mean was 14.6 ± s.d. 9.56 s (n = 60), excluding an aberrant whale discussed below. These values were somewhat longer than those observed from the air (13.0 ± s.d. 8.38 s, n = 2067), although the difference is not statistically significant.

Swimming Speeds

Since the theodolite supplied us with locations, we were able to calculate the speed of travel of some whales. Whales rarely changed direction within any one 30 s period, and we therefore calculated speeds from

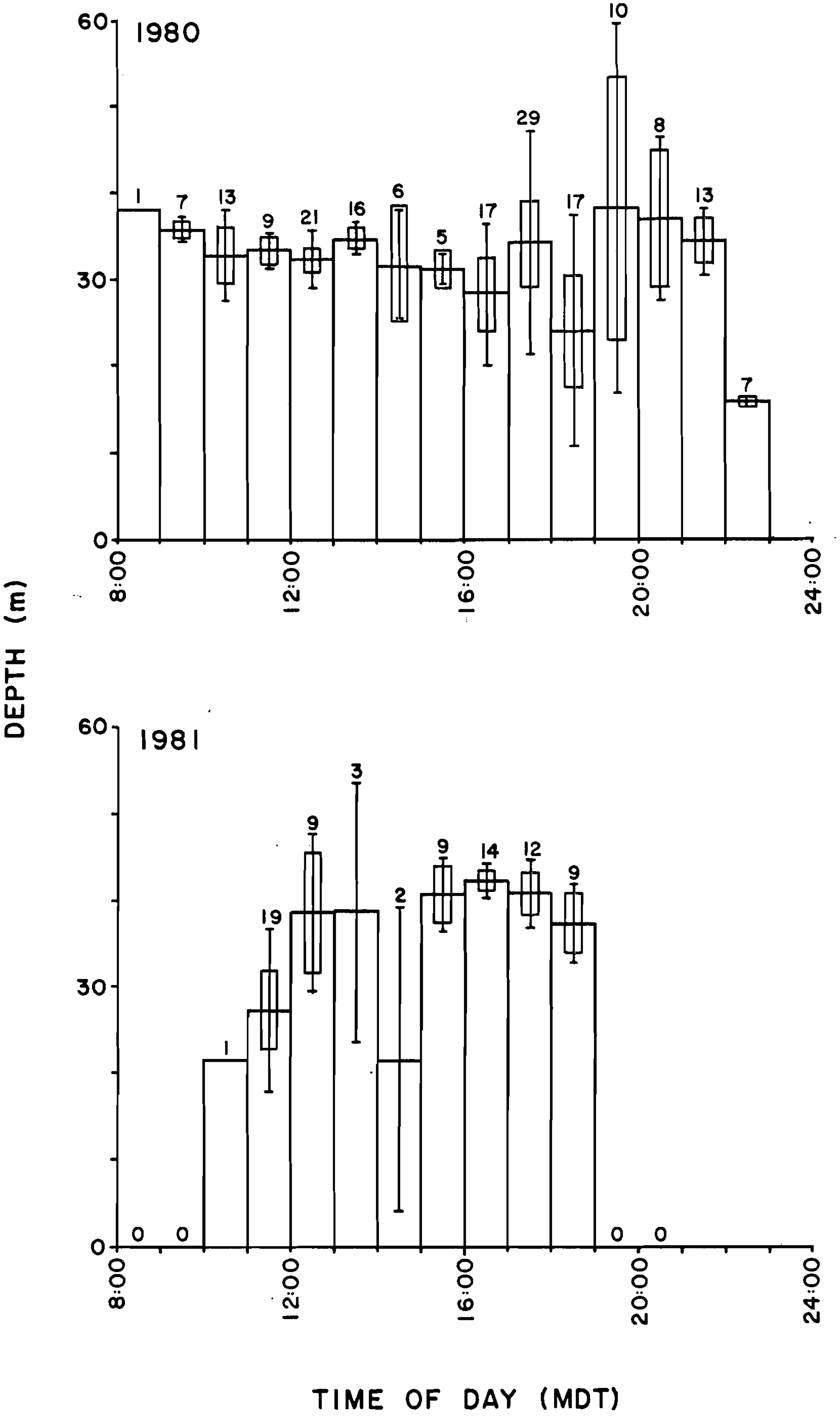


FIGURE 29. Depths of ocean frequented by whales near Herschel Island in relation to time of day, 3-12 September 1980 and 29 August-10 September 1981. Presentation as in Figure 12.

theodolite readings taken within 30 s of each other. This criterion was changed to 60 s periods for 30 August 1981, when a whale was followed at the surface for a long period, and changed direction relatively little.

For 1980, the average speed of whale travel was 5.1 km/h (n = 18, s.d. = 2.93) at the surface, and 4.3 km/h (n = 4, s.d. = 0.79) below the surface. Except during several unique situations (see below), we were unable to obtain average speeds of travel for 1981. The 1980 speeds are comparable to the most reliable estimates derived by Braham et al. (1979) and Rugh and Cubbage (1980) for migrating bowheads, 4.8 to 5.9 km/h and 4.7 ± s.d. 0.6 km/h, respectively. However, based on additional data, Braham et al. (1980b) estimated the mean speed at Point Barrow in spring to be 3.1 ± s.d. 2.7 km/h. The speeds of bowheads in active migration along the coast of Baffin Island in fall were 5.0 ± s.d. 1.3 km/h (n = 22) based on theodolite observations from a cliff, and 4.7 ± 1.6 km/h (n = 10) based on aerial observations (Koski and Davis 1980).

On 30 August 1981, an adult whale was observed continuously for 1 h 31 min. Its behavior was unusual in that it did not submerge during the entire time. (The longest surfacing that we observed otherwise in both years was 5.9 min.) This whale travelled in an easterly direction at an average speed of 2.3 ± s.d. 1.26 km/h, considerably slower than the speeds mentioned above. Its mean blow interval was 10.0 ± s.d. 13.55 s (n = 420), significantly lower than the mean for all other undisturbed whales observed from Herschel Island ($t = 3.26$, $df = 478$, $p<0.01$).

On 8 September 1981, data were collected by theodolite on a mother-calf pair for 1 h 49 min. Because we obtained only a few position readings of the adult during this time, no speed of movement could be calculated for the presumed female. However, the average speed of travel by the calf was 8.9 ± s.d. 5.57 km/h (n = 28). During this rapid movement, the calf exhibited several aerial behaviors: full breaches (exposing more than half the body out of water), half breaches (exposing less than half the body), forward lunges, tail slaps, flipper slaps, and head raises. Because such a sequence of aerial behavior has not been documented in detail for bowhead whale calves, we endeavor to do so below.

Calf Breaching*

The calf mentioned above was aerially active for 29 min. It breached 23 times, forward lunged 9 times, and half breached 5 times. These 37 events occurred in 10 discrete bouts that were separated by a mean of 1.83 ± s.d. 0.66 min (n = 9) between the last event of one bout and the first event of the next. Bouts were defined as series of successive aerial behaviors uninterrupted by a period of respiration.

The percentage of breaches in the total number of breach events (breaches + half-breaches + forward lunges) declined from 90% in the first five bouts (20 events) to 29% in the second five bouts (17 events) (Fig. 30). Since half-breaches and forward lunges are partial breaches, presumably not requiring as much exertion as full breaches, this decrease in the proportion of breaches may have been a result of the calf tiring. Southern right whale calves and adults also combine breaches, half-breaches and forward lunges, with the proportion of breaches varying considerably (0-86% for calves and 40-100% for mothers (P. Thomas and S. Taber, unpubl. data).

The calf's speed was highly variable during this aerial activity. The average speed between breaches was 5.5 ± s.d. 3.98 km/h (n = 10). The average speed between forward lunges and other aerial activity was 12.1 ± s.d. 6.14 km/h (n = 11). The difference in speeds between these two different behavioral categories was significant (t = 2.90, df = 19, p<0.01). The highest speeds recorded were 22.7 and 22.1 km/h, respectively, between breaches 1 and 2 and breaches 2 and 3 of bout 3. A speed of over 22 km/h was maintained for 61 s, during which the calf breached, travelled 190 m, breached again, changed direction by 165°, travelled 190 m, and breached a third time. These observations demonstrate the strenuous nature of breaching.

The mean time between aerial events in a bout was 28.1 ± s.d. 6.99 s (n = 36). The longest time between breaches was 43 s and the shortest 16 s.

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* This section was prepared by Peter O. Thomas, and may be cited as Thomas, P.O. 1982. Calf breaching. p. 126-130 In: W.J. Richardson (ed.), Behavior, disturbance responses and feeding of bowhead whales *Balaena mysticetus* in the Beaufort Sea, 1980-81.

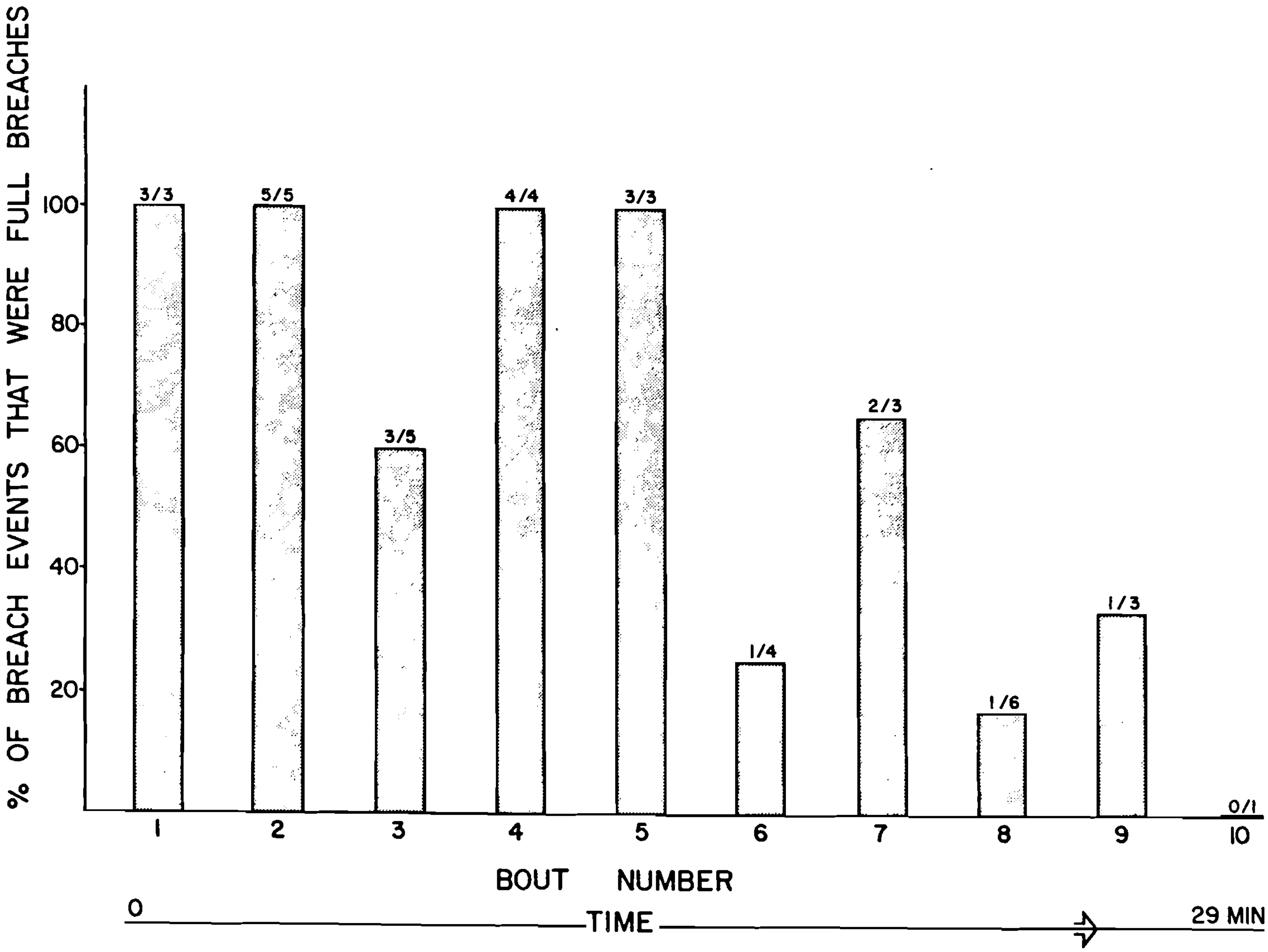

FIGURE 30. Breaches as a percent of all aerial events (breaches, lunges and half breaches) during each bout of aerial behavior of a bowhead calf, 8 September 1981, off Herschel Island.

In contrast, the breaches of an adult bowhead seen in 1980 were spaced an average of 45.5 s apart, and the mean time between aerial events for right whale calves ranged from 11-27 s in 8 different aerial sequences observed.

Between bouts the calf was observed to breathe from 0 to 4 times. Breaths could certainly have been missed, especially between bout six and seven when two surfacings were seen but no breaths were recorded in the 2.12 min between aerial events. Breaths between bouts were often taken with a sharp raise of the head. At the end of two bouts the calf slapped its flukes and at the end of another it slapped a flipper. Southern right whale calves commonly combine bouts of breaching with flipper and fluke slapping (Thomas and Taber, in prep.).

During this period of aerial activity the calf's track was very convoluted. Turns of more than 90° occurred between 10 of the events and similar changes of course occurred in the intervals between bouts (Fig. 31). In 7 of 10 bouts the calf changed direction after one or more breaches to bring it back toward the starting point of that bout. In six of these bouts the calf's last breach event was closer to the starting point than at least one of the middle breach events of the bout. This pattern resembles that of right whale calves, which often breached in 'circles' away from and then back toward their mothers (Thomas and Taber, in prep.). By contrast, the course of a right whale adult during a bout of breaching is usually straighter.

The adult thought to be the mother of the calf was within a few whale lengths of the calf when the calf first began to breach. But toward the end of the observation sequence, the calf was approximately 1 km from that location. At that point the calf stopped its aerial activity and rapidly, at a speed of 22.7 km/h, headed back in the general direction of the adult. Unfortunately the calf was lost to view because it stopped its aerial activity, but the movement toward the approximate adult position indicates that the two may have been in acoustic contact at a distance of about 1 km.

The right whale calves observed breaching in similar series of bouts were 1-4 months old (Thomas and Taber, in prep.). Calves 4-12 mo old were not observed in that study, so no conclusions can be drawn as to whether the 'circular' aspect of calf breaching is limited to an early age, or as to the

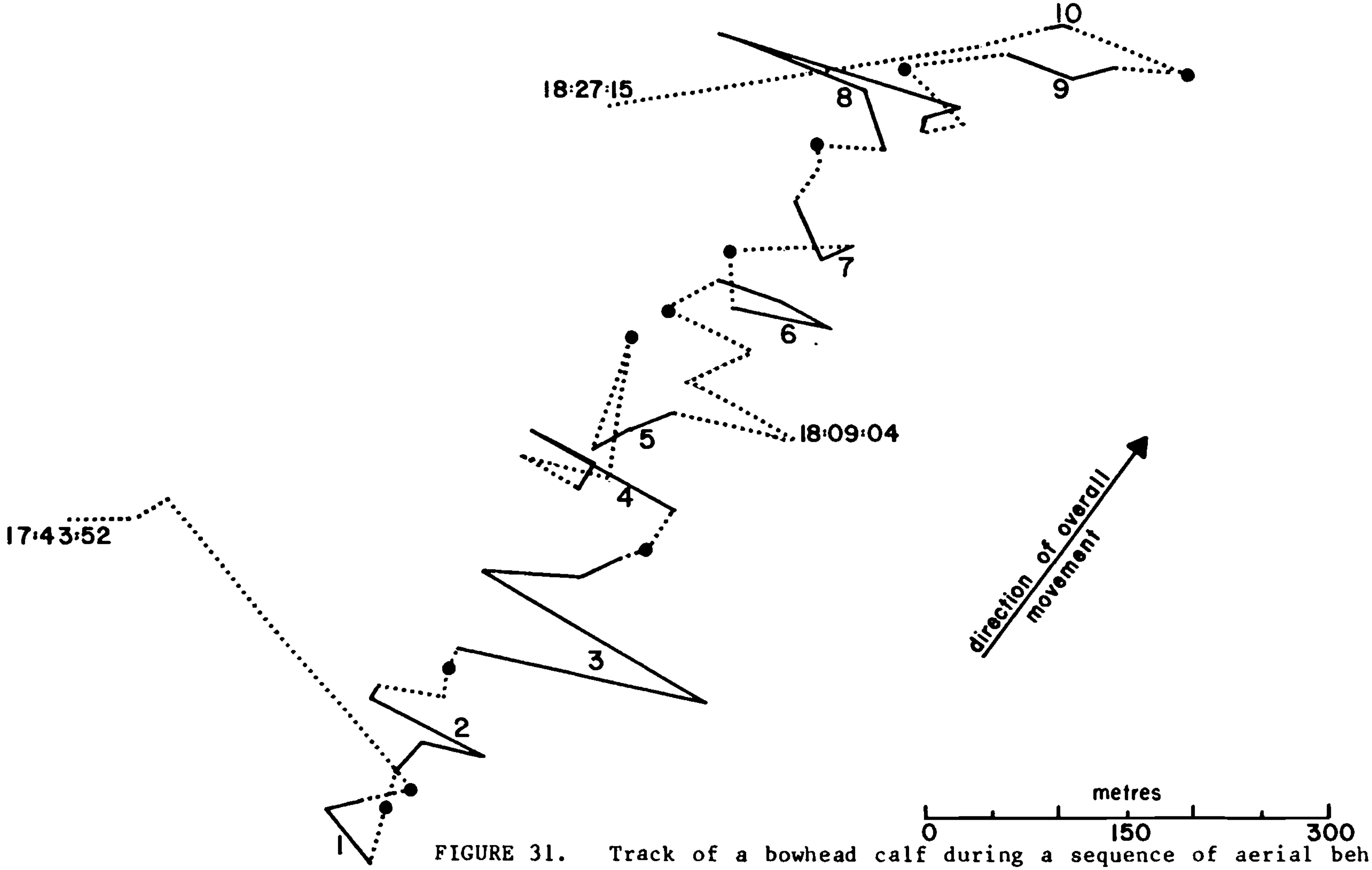

FIGURE 31. Track of a bowhead calf during a sequence of aerial behavior, 8 September 1981, off Herschel Island. Solid lines connect consecutive locations of aerial events. Numbers represent bout number. Large dots indicate submergence immediately prior to an aerial event.

age when a change from breaching in circular bouts to straight bouts might occur. We suspect that breaching in 'circles' originally functions to maintain proximity with the mother and would probably not be seen after the calf separates from its mother.

Straightness of Tracks

In the Herschel Island area, bowheads appeared to remain in the area for significant periods; they were not migrating rapidly through the area in either year. An index of milling (meandering index) was devised in order to calculate how much of an animal's movement was on a direct course, and how much was spent wandering about the same area. This index, which was similar to the 'swimming score' of Clark and Clark (1980), was calculated for each particular whale by dividing the distance between the first and last known positions (distance made good) during an observation session by the total length of its track. Whales travelling in a straight line would show an index approaching 1.0; whales milling in an area would show an index approaching 0.0.

In the present case, whales did meander, but also showed appreciable net motion from 6 to 11 September 1980 (meandering index = 0.70, s.d. = 0.238, n = 20). Because we have no comparable data on non-disturbed and normally surfacing whales in 1981, we also have no overall meandering index. The meandering index for the lone whale which travelled at the surface for over 1 h on 30 August 1981 was 0.63, a value just slightly below the mean from the previous year. This whale travelled a rather straight course during the time it was transited at the surface. The meandering index for the presumed female with calf nearby, observed on 8 September 1981, was 0.50. The highly active calf (see above) showed a low meandering index (0.12) because it reversed direction often and ended up only about 700 m from where it first began its activity.

Relationships to Ice

During 1980, whales were usually encountered in open water close to shore, and we made few excursions to the loose ice which was generally >50 km offshore. In 1981, especially in late July and early August, bowheads were not found close to shore. We often flew far offshore to the edge of the pack ice, and we often encountered bowheads just south of and in the ice.

In late July and early August 1981, we flew long distances over open water north of the Tuktoyaktuk Peninsula and Mackenzie Delta, and saw virtually no bowheads except in a zone 0-20 km south of the southern edge of the pan ice (see Davis et al. 1982 for distributional data). Most notably, on each of 4 and 5 August we found at least 40 bowheads near 70°50'N, 135°10'W, which was in this zone just south of the ice. At this time bowheads were also present in the partially ice-covered area farther north. Within the ice, the usual ice cover where whales were seen was 10%, but on 12 August 1981 we encountered a whale in 55% ice. This should not be taken as indicative of the ice conditions preferred by bowheads, since we rarely flew over the heavier ice. In mid and late August 1981, bowheads moved farther south and well away from the ice, and we rarely searched for them in ice-covered areas.

Most whales encountered near pans of ice were quiescent at the surface. Whales that were moving among ice pans usually did not go around the pans, but instead dove underneath the ice. On several occasions we saw whales dive below a pan and then come to the surface on the other side, without an apparent change in direction.

During the first and second week of September 1980, and during the entire observation time in 1981, loose pan ice occurred off Herschel Island. At times, over 50% of the area was covered by ice, and some whales were separated from ice by no more than several metres.

Interspecific Interactions

A few species occurred in the same general areas where we observed bowheads: ringed seals (Phoca hispida), white whales (Delphinapterus leucas), gulls and phalaropes--probably northern phalaropes (Lobipes lobatus). Although ringed seals and white whales were present in the same general area as bowheads, there was no obvious interaction. However, the seals may have been feeding on some of the same organisms as the whales, or on other organisms (e.g., fish) that were feeding on the same species as the whales.

It seems unlikely that the seals would feed on copepods, but Lowry et al. (1978) found larger zooplankton--euphausiids and amphipods--in the stomachs of both ringed seals and bowhead whales that had been taken in Alaskan waters.

Flocks of up to 50 phalaropes were often present near skim-feeding bowheads. Often the birds alighted on water that had been disturbed by the whales, sometimes only a few metres from the whales. These birds probably were feeding on some of the same plankton species that the bowheads were eating. The whalers often used the presence of phalaropes as an indicator of where 'whale feed' was present, and therefore, where whales were likely to be found (J.R. Bockstoce, Old Dartmouth Historical Society, pers. comm.). We observed gulls near bowheads on three days in 1980, but not in 1981.

Comparisons with Other Cetaceans

Inasmuch as our task was to assess normal behavior and (in other sections of the report) disturbance, the observer problem--the effect of the observer on the natural behavior he seeks to observe--was of particular concern to us. Thus, our results might have been affected by the presence of the aircraft or boat used for making observations. In the case of boats, this was not a problem when the observation boat itself was used for the disturbance trials. When used for observations of undisturbed behavior, the boat had to be kept at a distance with the engine off. In the case of the aircraft, the disturbance problem was more serious than we expected. Bowheads often reacted strongly to the aircraft when it circled at 305 m ASL. We found that as long as we stayed at or above 610 m we did not affect the whales' behavior noticeably but that at 457 m there were at least some subtle effects on surfacing and respiration patterns (see 'Disturbance' section, Fraker et al. 1982). Even if 457 m is taken as the minimum usable altitude, this is three or more times higher than the altitudes suggested by others for studying undisturbed behavior of other whale species (Herman and Antinoja 1977; Watkins and Schevill 1979). Payne (unpubl.) has found, in detailed studies of the closely related southern right whale, that light aircraft at altitudes above 100 m do not appear to disturb any but a very few individuals. Payne had an independent check on the effects of aerial observations because he was able to compare his aerial data with observations from shore.

Because whales need to come to the surface to breathe, there are broad similarities in surfacing and diving characteristics for all species. During most activities, whales respire several times (usually about 4-10 times) between long dives. Most whales submerge for brief periods within the sequence of respirations between the long dives. This is especially true during directed movement such as migration. This basic pattern of surfacing-dive-surfacing sometimes breaks down, especially in humpback, gray, right, and bowhead whales during periods of active socializing near the surface. While the sleek rorquals (Balaenopterid whales) are in general pelagic, feeding actively on schools of fish in deep water, the gray (Eschrichtid) and right (Balaenid) whale types spend much time nearshore, especially during the mating/calving season. These latter animals do not pursue their prey actively, but instead feed on relatively stationary small prey in generally shallow waters. Because of these basic similarities (and there are morphologic similarities paralleling the ecological ones), we can expect to find less behavioral variation between these species than between bowhead whales and rorquals. A review of the literature confirms these impressions (for example, Gunther [1949] on fin whales; Notarbartolo di Sciara [in press] on Bryde's whales; Herman and Antinoja [1977] on humpback whales; Frazer [1976], Watkins and Schevill [1979], Lockyer and Brown [1981] on comparisons of many species).

The similarities in behavior between bowhead whales and the closely related right whales are especially noteworthy. Thus, Best (1981) describes the fragmentation and amalgamation of groups of South African right whales on the breeding grounds in a similar manner as we observed for bowhead whales on the feeding grounds. Personal observations by three of us (BW, CWC, RSP) of South American right whales show similar variations in group structure to those described by Best. Unfortunately, too few data are available on surfacing and respiration characteristics of right whales to allow a detailed comparison of the two species. However, right whales spend longer times at the surface when socializing than at other times, just as bowheads appear to do.

Feeding by bowhead and right whales appears to be quite similar. Watkins and Schevill (1979) described right whales feeding on plankton concentrations in the North Atlantic by skimming with mouths open wide just under the surface; they also believed that feeding occurred well below the surface at times, as evidenced by acoustic data gathered on whales diving down to discrete patches of plankton (Watkins and Schevill 1972, 1976). Our observations of bowheads feeding near the surface are similar, and there was evidence of an unusual abundance of copepods near the surface on one of these occasions. We observed whales feeding near the surface in echelon formation, a behavior also seen in southern right whales (RSP, CWC, BW, pers. obs.) although not reported by Watkins and Schevill in northern right whales.

We believe that bowheads, like the right whales studied by Watkins and Schevill, were feeding in the water column during many of their dives. However, we do not have direct proof that they did so. We also do not have information about plankton concentration at the exact mid-water locations where bowheads were presumed to feed. However, there was evidence that they tended to occur in general areas with higher than average biomass of copepods (Griffiths and Buchanan 1982).

Best (1981) describes right whales trailing upwellings of bottom sediment in shallow water, much as we observed during 'mud-tracking'. However, we also saw bowheads apparently feeding near the bottom, as evidenced by muddy water streaming from their mouths, and we saw them blowing underwater. These two activities have not been described in right whales (but right whales have been little studied during the summer feeding period).

Some of the most dramatic similarities between bowhead and right whales involved socializing at the surface, and possible precopulatory behavior. Donnelly (1967, 1969), Payne (1972), Saayman and Tayler (1973), and Best (1981) have all described behavior of southern right whales related to courtship. This activity is similar to the few possible examples of precopulatory behavior that we witnessed. Best (1981) has recently linked the mating behavior of the two species from his observations of southern right whales and his interpretation of a bowhead mating sequence described by Everitt and Krogman (1979). The social behavior that we observed--pushing and nudging, chases, apparent mating--looked similar to, although was seldom as boisterous as, that seen in right whales. We conjecture that the difference in level (but not kind) of activity is mainly attributable to seasonal differences: although both right and bowhead whales engage in social and feeding activities during much of the year, they feed most often in the summer and perhaps autumn, and probably mate and calve at other times. Although the behavioral components of precopulatory activity are sometimes evident in bowheads in summer, this activity was neither as frequent nor as intense as during the primary mating period, which includes spring migration (Everitt and Krogman 1979; Carroll and Smithhisler 1980; Johnson et al. 1981; Ljungblad 1981).

We also saw similar aerial activity (breaching and tail and flipper slapping) in right and bowhead whales, though not as much as among right whales on their breeding grounds, where breaching can lead to breaching by others, and may serve as a communication device between whales (Payne 1976). These differences in quantity may again be related to the seasonal difference in the observations of bowheads and right whales. Gray whales in calving lagoons of Baja California apparently breach by social influence (Norris et al. in press). Humpback whales in southeastern Alaska may do so as well, and in contrast to bowhead whales, are quite aerially active while feeding (Jurasz and Jurasz 1979).

All of these observations require amplification in bowheads, but at their present state they suggest a strong and not unexpected similarity to the closely related right whale. This suggests that it may prove possible, as more data become available, to predict or extrapolate from the right whale model to the behavior of bowheads, or vice versa. At any rate, the two can be profitably compared and contrasted. This may be especially true in assessing the sounds of the two species. Clark (1982a) has catalogued major sounds of right whales according to different behaviors. In the present study we have found similarities and some minor differences between bowhead sounds and those of right whales. We have also found evidence of similarities in the contexts of some analogous call types by bowheads and right whales. More information about the significance of each call type to the bowhead is needed before meaningful conclusions can be drawn, but this approach should ultimately provide a basis for assessing the effects of masking of acoustic communication.

Present Results and the Alaskan Lease Area

The degree of similarity between bowhead behavior in the Canadian Beaufort Sea in summer and in the Alaskan lease areas during spring and fall migration is not well known, but there is now sufficient evidence to allow a preliminary comparison. During the present study bowheads appeared to spend much of their time feeding, but also travelled frequently and for considerable distances. Bowheads often loiter for considerable periods in the Alaskan Beaufort Sea during autumn, and at least some feeding occurs in autumn just west of the Alaska-Yukon border (Ljungblad et al. 1980b; Lowry and Burns 1980; Ljungblad 1981). Feeding apparently also occurs just east of Point Barrow and off the Soviet coast in autumn (Braham et al. 1977; Lowry et al. 1978; Johnson et al. 1981). Nonetheless, it is probable that the whales are feeding less during the autumn migration than when they are summering in the eastern Beaufort Sea, and it is known that they rarely feed during the spring migration around northwestern Alaska. Although social and sexual activities are probably most frequent earlier in the year before the animals arrive in the Beaufort Sea, we did see much socializing and some evidence for mating behavior during the summer. Also, call types in spring and summer have been shown to be the same. Thus it appears that the relative rates of various behaviors differ among spring, summer and autumn, but that behavior is qualitatively similar, at least in summer and autumn.

Our observations of bowheads on their summering grounds in the eastern Beaufort Sea showed many similarities of behavior to southern right whales on their wintering grounds (when little feeding but much socializing, mating, and calving takes place). This may also shed some light on the question of applicability of our research to the Alaskan lease areas. If we find such dramatic similarities in behavior between different species in different hemispheres during different seasons, it seems likely that we should find at least as many similarities between seasons within the same species.

Based on these preliminary comparisons and analogies, we believe that bowhead behavior is likely similar in summer (when we have studied it) and in autumn (when bowheads pass through the Alaskan Beaufort lease areas). There may be less similarity between spring and summer because of the greater rapidity of the spring migration, the lack of feeding, and the presence of ice. To resolve this question, at least a limited program of behavioral observations should be conducted in Alaskan waters in spring and autumn using techniques comparable to those used here. Preliminary observations of this type were obtained in the Alaskan Beaufort Sea in September-October 1981, and results will soon be forthcoming (LGL in prep.).

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DISTURBANCE RESPONSES OF BOWHEADS*

By

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ABSTRACT

Studies of the behavioral responses of bowhead whales to activities associated with offshore oil and gas exploration and development were conducted in the eastern (Canadian) Beaufort Sea during the summers of 1980 and 1981. Both experimental and observational approaches were used. Noise is believed to be the by-product of normal industrial operations that may be most likely to affect whales significantly. Hence, we recorded and analyzed the underwater sounds from several vessels, aircraft, seismic exploration, and dredging and drillship operations. Most of the energy contained in sounds from the above sources was below 2000 Hz, as is most energy in sounds made by bowheads (see companion reports on 'Industrial Noise' by Greene 1982 and on 'Normal Behavior' by Würsig et al. 1982).

Bowheads responded to **boats** in two main ways. (1) When boats were nearby, bowheads altered their surfacing and diving pattern by decreasing the mean time at the surface per surfacing, the mean number of blows per surfacing, and the mean dive duration. Mean surface times and blows/surfacing were reduced even in response to a stationary 16 m boat with its engines idling at a range of 3-4 km. (2) When boats closed to within 1-3 km, the whales, in addition to the above responses, swam rapidly away from the boat and scattered. Whales directly on the boat's track initially tried to outrun it, but usually turned to move off the track as the boat closed to within a few hundred metres. None of the boat disturbances that we observed resulted in the whales' leaving an area; however, the effects of more frequent boat disturbance are unknown.

Bowheads typically dove in response to our Islander observation **aircraft** when it circled above the whales at $\leq$305 m above sea level (ASL). They occasionally dove in response to the aircraft when we circled at 457 m. Considering all data collected in 1980-81, mean surface times were slightly reduced when the aircraft circled at 457 m relative to those when it circled at 610 m, but there was no evidence of an effect on respiration or dive characteristics. On two days when a group of whales was circled at 610 m and then at 457 and/or 305 m, there were clear effects on respiration when the aircraft descended. In general, reactions to a circling aircraft were

conspicuous if it was at 305 m, minor at 457 m, and absent or undetectable at 610 m.

Underwater noise from a Bell 212 helicopter was stronger than that from the Islander. Thus, reactions of bowheads to such a helicopter would probably be stronger than those to the Islander. However, during straight-line passes at 152-610 m ASL over a hydrophone, helicopter sound was detectable for only 16-27 s.

Noise from **seismic exploration** is by far the most intense noise in the Beaufort Sea, although it is not continuous. In 1980 and 1981 we saw bowheads as close as 13 and 6-8 km, respectively, from a seismic ship that was firing 12 large sleeve exploders. Seismic signal levels at those ranges were 141 and 150 dB//1 µPa. Surfacing and respiration behavior at 13 and 8 km from the seismic ship was similar to that at corresponding water depths in the absence of seismic noise. Industry personnel reported sightings of bowheads 2-7 km from a seismic ship that uses airguns. Sonobuoys showed that bowheads often continued to call in the presence of seismic noise.

During a controlled experiment with one 40 in^3 (655 cm^3) airgun 5 km from bowheads engaged in echelon-feeding, we found significantly reduced surface times, blows/surfacing and calling rate, and possibly reduced dive times and echelon sizes. The airgun was fired every 10 s for 20 min, and near the whales the signal level from the airgun was at least 123 dB//1 µPa. No unambiguous behavioral effects were demonstrated during a second airgun experiment 3 km from whales, and there was circumstantial evidence of habituation to seismic noise. If bowheads react to the onset of noise from one airgun 5 km away, as our results suggest, they can be expected to react to the onset of full-scale seismic operations 20 km away in our shallow study area, and possibly farther away in a deeper area where sound propagation is better.

In 1980, bowheads frequently were seen <5 km from an artificial island that was under construction by a **dredge**; LGL personnel saw bowheads as close as 800 m from the operation, and industry personnel reported that one bowhead came as close as 16 m from a barge near the dredge. Sounds from the dredge were well above ambient levels, and almost certainly audible to bowheads, out to at least 7.4 km.

We saw bowheads as close as 4 km from a drillship, and industry personnel reported closer sightings. The strongest tonal sound from the drillship (278 Hz) was about 111 dB//1 µPa at 4 km from the ship. It is uncertain whether behavior was affected by the presence of the drillship. Respiration and diving behavior 4 km from the drillship differed from that in the absence of the drillship, but also differed from behavior with boat or airgun disturbance.

INTRODUCTION

Concern about possible adverse effects of offshore oil and gas development activities on cetaceans has increased greatly in recent years. Uncertainty about the effects on the bowhead whale, Balaena mysticetus, officially an endangered species, is a major concern with respect to the existing and proposed lease areas in the Alaskan Beaufort Sea. This concern probably will be raised again as other offshore areas in the Chukchi and Bering Seas are offered for lease.

Marine mammals (including bowheads) use sound to communicate and to receive information about their environment. In contrast to light, sound travels very efficiently in water, day or night, winter or summer, and regardless of the water's clarity. The intense, low-frequency sounds produced by baleen whales, including bowheads, are transmitted considerable distances in deep water (Payne and Webb 1971). The very advantages of underwater sound that have been so useful to marine mammals give rise to potential problems related to underwater industrial sounds (Acoustical Society of America 1981). Many industrial sounds are also intense and of low frequency, and consequently are transmitted efficiently over relatively long distances. Thus, the acoustical effects of industrial operations may be manifested considerable distances from their sources, and this greatly expands the area affected. Possible ways in which underwater industrial sounds could affect whales include inducement of behavioral responses or stress, and the masking of important communication, echolocation and/or environmental sounds.

In addition to underwater sound, it is possible that the physical presence of various sorts of structures might be detected, visually or by touch, or that various effluents that are discharged into the water might be sensed by the whales. Although it is generally agreed that underwater sound has the greatest potential zone of influence on whales, other stimuli from offshore oil and gas activities may also have some effect.

This project, as a whole, was designed to gather data that will improve the general understanding of the behavior and ecology of the bowhead whale, and its responses to offshore industrial activities (see 'Project Rationale, Design and Summary' section, Richardson and Fraker 1982). The emphasis in this component was on the behavioral effects of waterborne sound per se, and on the effects of vessels and machinery that produce waterborne sounds (e.g., boats, aircraft and dredges). In the latter cases, responses to sound are likely to be a major part of the overall response, but response to 'physical presence' usually cannot be ruled out. This section is based on systematic experiments designed to test the behavioral responses of bowheads to various sources of potential disturbance, and on observations of the presence and behavior of bowheads near vessels and ongoing offshore industrial activities. Measurement of the characteristics of industrial noise was an integral part of the work; the following section on 'Industrial Noise' (Greene 1982) describes those results. The preceding section, 'Normal Behavior' (Würsig et al. 1982), describes complementary studies of the undisturbed behavior of the bowhead, and a later section, 'Feeding Areas' (Griffiths and Buchanan 1982), describes characteristics of bowhead feeding areas in the eastern Beaufort Sea.

For reasons described in the 'Project Rationale, Design and Summary' section, the work on all components of the study was conducted in the eastern (Canadian) part of the Beaufort Sea. The present report is an integrated account of results obtained in 1980 and 1981, and supersedes our preliminary account of the 1980 work (Fraker et al. 1981).

Offshore Exploratory Activities in the Eastern Beaufort Sea

Our studies in both 1980 and 1981 were based at Tuktoyaktuk, Northwest Territories--the base of operations for offshore oil and gas exploration in the eastern Beaufort Sea (Fig. 1). These operations provide opportunities to observe the reactions of bowheads to full-scale offshore exploration. The main offshore operators are Dome Petroleum Ltd. and Esso Resources Canada Ltd.

During the 1980 and 1981 study periods Dome, through its subsidiary Canmar, operated four drillships and a fleet of supply and auxiliary vessels. Helicopters frequently travelled between Tuktoyaktuk and the drillships. The drillships usually drill in water 20 to 100 m in depth. Three or four drillships have been used during the summer and autumn of each

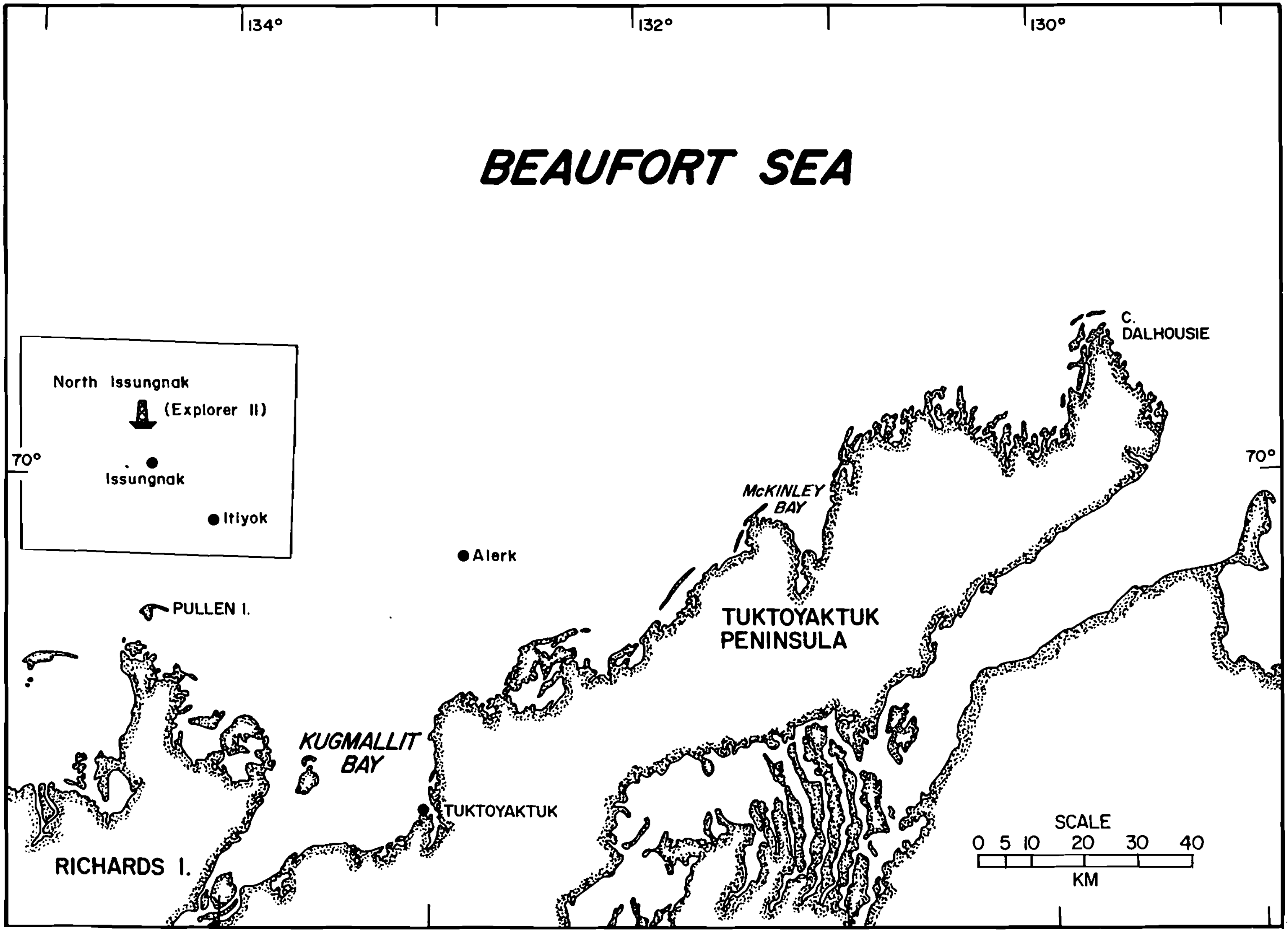

FIGURE 1. The eastern Beaufort Sea region, showing locations mentioned in the text. The rectangular area is the area around the Issungnak artificial island site where systematic aerial surveys were flown on four dates in August 1980.

year since 1976. In addition, Dome began to drill from its first artificial island late in 1981, after our field season ended.

Esso's offshore activities center around the construction of man-made islands which are used as platforms for exploration drilling. Most islands have been built during the open-water period, although some were built during winter. Initially the islands were built in shallow (1-9 m) water, but during 1977-81 islands were constructed in water 13-19 m deep. Most of the material for the latter islands was dredged from around the island sites by the suction dredge 'Beaver Mackenzie'. In 1980, an island at Issungnak (19 m depth) was completed and another at Alerk (13 m depth) was begun. In 1981, Alerk was completed and another island, Itiyok, was begun. In addition to the dredge, the operation typically included four tugs, two crew boats, various barges, and a barge camp. No drilling from artificial islands took place during either of our field seasons.

In addition to drilling operations, ship-based underwater seismic exploration took place in the eastern Beaufort Sea during the open water season. Dome used an 'airgun' array; each airgun releases a charge of compressed air as the energy source (Barger and Hamblen 1980). In 1980 and 1981, Esso used a set of 12 'sleeve exploders', which are very strong rubber cylinders into which a charge of propane and oxygen is injected and ignited by an electric spark. The rapid combustion produces the required energy pulse, and the exhaust gases are vented to the surface through a hose. Seismic exploration produces very intense pulses of waterborne noise (Greene 1982).

Additional information about ongoing and planned offshore exploration and development in the Canadian and Alaskan Beaufort Sea, emphasizing aspects relevant to potential impacts on bowhead whales, appears in Fraker and Richardson (1980).

Review of Previously Existing Knowledge

The literature on possible effects of offshore marine operations on whales is extremely limited. This is a result of the difficulties inherent in studying whale behavior and, until recently, the almost complete lack of perception of any potential for adverse effects from marine industrial operations (except, perhaps, a major oil spill or the tropical tuna fishery with its incidental kill of porpoises). As mentioned above, it is generally agreed that underwater sound is the by-product of normal marine operations that holds the greatest potential for affecting whales.

Most situations in which whales may have been disturbed have not been studied in sufficient detail to show whether or how the whales have been affected. The following subsections, largely abbreviated from Fraker and Richardson (1980), summarize the available information.

Effects of Marine Traffic

To date, marine traffic is the main type of offshore industrial activity that has been implicated in causing disturbance to cetaceans. The known or suspected types of proximate effects can be classified into five categories: (1) fright/flight responses, (2) sonar-reflecting barriers, (3) territorial intrusion, (4) masking of important sounds, and (5) general disturbance (without any of the above effects).

Fright/flight responses have been reported on several occasions for white whales (Delphinapterus leucas) in the Mackenzie estuary, for porpoises (Stenella spp.) in the tropical Pacific, for dolphins (Tursiops truncatus) off Florida, and for sperm whales (Physeter macrocephalus), fin whales (Balaenoptera physalus) and humpback whales (Megaptera novaeangliae). In each of these cases, the animals appeared to be responding to waterborne sound from vessels.

Norris et al. (1978) studied the behavior of porpoises in relation to tuna fishing operations. When the seiner approached to within 5-7 km, the porpoises responded by moving closer to each other (i.e. the school 'tightened') and by moving away from the seiner; when the seiner stopped, the porpoises stopped and spread out once more. At a distance of 5-7 km the seiner probably was not visible to the porpoises and the response must have resulted from underwater sound from the seiner. It is presumed that the porpoises had previously encountered tuna seining operations and associated the sound of a seiner with an unpleasant experience (W.E. Stuntz, U.S. Nat.

Marine Fisheries Service, pers. comm.). Irvine et al. (1981) found that bottlenose dolphins not previously captured did not attempt to avoid the 7.3-m tagging/observation boat, but once captured and released they subsequently began fleeing 400 m or more ahead of the boat.

In the shallow water (usually <2 m) of the Mackenzie River estuary in the Beaufort Sea, white whales gather in large numbers during summer. Fraker (1977a, b, 1978) and Fraker et al. (1978) have reported instances in which white whales responded to boat traffic at distances up to 2.4 km. In one instance, a barge tow passed through a large concentration of whales, splitting it into two (Fraker 1977a). Without exception, the whales responded by moving away from the barge track at distances up to 2.4 km from the barge tow. The group remained split for at least 3 h, but rejoined within 30 h when the next survey was possible.

Complementary underwater sound source measurements and propagation studies indicated that white whales probably could perceive the sounds from tugs at ranges up to 2.5-3.0 km (Ford 1977). The waterborne noise emanated from the tug with source levels of up to 164 dB re 1 µPa at 1 m. Ambient underwater noise under calm conditions in the Mackenzie estuary measured 50 to 60 dB re 1 µPa. Measurements of sound propagation and attenuation showed that tugboat sounds declined to quiet ambient levels at 4.0 to 6.0 km, depending on the water depth. (The shallow water and soft sediment bottom resulted in rapid attenuation of sound.) Most of the sound energy produced by the tugs was at frequencies below 2000 Hz.

Disturbance necessarily attends whale tagging operations. As noted above, Irvine et al. (1981) found that *Tursiops* became sensitized to noise from a boat used in previous capture attempts. Ray et al. (1978) recorded the breathing behavior of fin whales before, during, and at some time after a chase and tagging operation. The effect of the disturbance during and after tagging on the breathing pattern was to reduce the time at the surface for each surfacing, the number of breaths per surfacing, and the 'down time' between surfacings. Watkins (1981) and Watkins et al. (1981) mention that fin whales attempted to evade an approaching boat, but ignored boats from which observations were being made as long as the boats remained >100 m away. Watkins et al. also mention that feeding by humpback whales (and porpoises) was not disrupted by passage of a large oil tanker within 800 m.

Similarly, Bogoslovskaya et al. (1981) report that if a vessel is 350-550 m from gray whales (Eschrichtius robustus), 'they move off but stay in the same area; ...when being pursued animals cease feeding and try to leave the area'.

Whales do not always avoid boats. Among baleen whales, minke whales (Balaenoptera acutorostrata) seem particularly attracted to boats (Winn and Perkins 1976). Dahlheim et al. (1981) report that some gray whales in calving lagoons in Baja California are attracted by sounds from outboard motors. These whales '...actively seek out the sound source and physically contact slow (2-4 kts) moving small vessels (inflatable Avons, Zodiacs, wooden and aluminum skiffs). Engines kept in idle (running but out of gear) maintained these whales in close proximity for periods up to 3 hours...This "curious" behavior is prevalent only in areas where whales are repeatedly exposed to small vessel activity'. Dolphins commonly approach boats and swim in their bow waves, and Brodie (1981) mentions several situations in which baleen whales feed in close proximity to boats.

The creation of **sonar-reflecting barriers** is the second category of proximate effects of marine traffic. Stuntz et al. (1977) and Norris et al. (1978) have reported that porpoises fail to cross the wakes of boats involved in the tuna fishery. In fact, part of the strategy to herd the porpoises (and, therefore, tuna) is to maintain a 'barrier' of bubbles from the boat wakes. Norris et al. suspected that echolocation was the main sense involved in the detection of the boat wakes. Similarly, Fraker (1977a) noticed that white whales failed to cross a relatively heavily used barge route in the Mackenzie estuary, and he (1977b) suggested that this apparent interruption in the movement of whales may have been due to the persistence of suspended air microbubbles, even when barges were not nearby. If this effect is based on echolocation, it probably would not be manifested in bowheads or other baleen whales. Current information on the vocalizations of bowhead whales (Ljungblad and Thompson 1979; Ljungblad et al. 1982) and baleen whales in general (Thompson et al. 1979) does not indicate the presence of any echolocation ability.

Territorial intrusion effects have been suggested by Jurasz and Jurasz (1979) as the mechanism by which humpback whales in the Glacier Bay region of SE Alaska have been affected by vessel traffic. Jurasz and Jurasz believe that the whales defend feeding territories from other whales. Various behaviors, such as underwater exhalation, lob-tailing and breaching, may serve as territorial displays. Jurasz and Jurasz believe that vocalization is the weakest form of threat display and that breaching is the strongest, with the others being intermediate. If, through displays, an intruder establishes his dominance over the defender, the defender will avoid the intruder and eventually may abandon the territory. Jurasz and Jurasz suspect that the whales perceive boats as other 'dominant' whales, and conclude that the humpbacks of Glacier Bay are so frequently confronted by dominant 'whales' (i.e. boats) that they now leave the area earlier in the season than they otherwise would. This interpretation is controversial (MMC 1979), and additional work on this problem is in progress.

Intense underwater industrial sounds have the capability of **masking** sounds that are important to whales (Møhl 1981; Terhune 1981). Important sounds would be mainly of three types: (1) communication sounds, (2) echolocation sounds (in toothed whales), and (3) environmental sounds that are useful to the whales. Loud, high-frequency sounds (not likely to be produced by most industrial sources) could interfere with the echolocation ability of toothed whales; this has been experimentally demonstrated by Penner and Kadane (1979).

It is also possible that industrial operations might result in **general disturbance** that could seriously disrupt important activities and/or cause abandonment of important habitats without producing any of the other effects mentioned above. For example, Herman et al. (1980) have suggested that humpback whales in Hawaii now avoid areas that were formerly used but that now have considerable marine activity. General disturbances might not frighten whales in any overt way or mask their communication signals, but might nonetheless adversely affect their normal use of important habitat.

Effects of Aircraft

Previous information on reactions of whales to aircraft is very limited. Bowheads on the Beaufort Sea summering ground did not appear to react to a survey aircraft (Twin Otter) flown at 305 m above sea level (ASL), but whales that were being circled and photographed responded in all cases by diving (M. Fraker, unpubl. data). During surveys in the Canadian eastern arctic (Davis and Koski 1980), bowheads overflown by a Twin Otter at 90 m almost always dove, whereas those overflown at 150 m usually did not dive during the first pass (W.R. Koski, LGL Ltd., pers. comm.); eastern arctic bowheads overflown or circled at 305 m often showed little or no discernible response, but systematic data are not available. Eastern arctic bowheads appeared less likely to dive when in pack ice or on summering grounds than when actively migrating, but again no systematic results are available.

In the Mackenzie estuary, aerial surveys of white whales conducted at 305 m ASL in a Cessna 185, a single-engine piston powered aircraft, appeared to result only in very occasional cases in which an animal rolled over in the water, apparently to follow the aircraft visually. However, circling at the same altitude, or surveys repeatedly flown over the same survey lines in a brief period of time (e.g., at intervals of approximately 0.5 h), resulted in an obvious response (LGL unpubl. data). In the case of repeated flights along the same flight lines, white whales apparently became more sensitive and began to swim away from the flight track. Animals being circled (at 305 m) appear to try to escape the area being surveyed, but the direction of movement is not predictable. When circling is necessary in order to observe the behavior of white whales undisturbed by the aircraft, we have used an altitude of 457 m.

In contrast, Watkins and Schevill (1979) report good success in observing the behavior of right whales and other baleen whales from light, single-engine aircraft off the Massachusetts coast. They were able to study the whales' feeding behavior at altitudes as low as 50 m under reduced power settings (which reduce the engine noise). Similarly, Baker and Herman (1981) flew at 152 m in light single-engine aircraft during surveys of humpback whales, and circled them (apparently at 152 m) to observe behavior.

Effects of Stationary Marine Industrial Activities

In general, stationary marine industrial activities appear to have a smaller effect on whales than do moving vessels. In several instances in the Mackenzie estuary, white whales were observed moving past a stationary dredging operation at ranges as close as 400 m (Fraker 1977a, b). However, in one case, as soon as a barge tow began to move toward the whales, they immediately moved away from the barge track. Industry personnel also reported that white whales closely approached the stationary dredge and barge camp. The waterborne sounds from the dredging operation were generally similar to those produced by boat traffic (Ford 1977). Peak source pressure levels were estimated to be 164 dB re 1 μPa at 1 m, and most of the energy was below 2500 Hz. The attenuation of these sounds with increasing distance was rapid and similar to that of the boat sounds.

During their twice-yearly migration, the entire population of California gray whales is exposed to considerable marine activity as they move along the west coast of North America. However, gray whales have apparently been displaced by industrial operations and shipping from certain calving lagoons (Reeves 1977) and it has been reported that gray whales may now migrate farther offshore than they did in the recent past (Rice 1965; Wolfson 1977). Gray whales have been exposed over more than a century to gradually increasing levels of sound from various marine activities. Despite this, the population size has increased and is now believed to be similar to the level before commercial whaling. It is not known whether the gradual nature of this increase in levels of disturbance has facilitated adjustment by the gray whales.

Observers on support ships stationed 'at or near' three drillships drilling in Davis Strait off the west coast of Greenland in the summer of 1977 saw totals of 59, 20, and 181 baleen whales in 83, 65, and 60 days, respectively (Kapel 1979). Most of these whales were fin, minke, and humpback whales, but one bowhead was identified. Unfortunately, the observation procedures, proximity of the whales to the drillships, and behavior of the whales were not reported.

Long-Term Effects

The ultimate effects of disturbance may be the abandonment of a particular area, and possibly reduced productivity and population size. There are a few known instances in which abandonment of a disturbed area may have occurred, and one in which this almost certainly did occur. The comparatively well-documented instance occurred in Black Warrior Lagoon, Baja California. Following an increase in shipping and other activity at salt works in the lagoon, the number of gray whales declined sharply. After operations ceased, the number of whales using the lagoon increased (Norris and Reeves 1977; Reeves 1977).

There are other less well-documented situations in which whales may have been displaced from certain areas by human activities, usually related to marine traffic. Spinner dolphins (Stenella longirostris) may have been displaced from a bay in Hawaii by marine construction activities (Shallenberger 1977). Humpback whales may have abandoned certain Hawaiian waters because of heavy interference by human activities, but the evidence is weak (Norris and Reeves 1977; Herman 1979; Herman et al. 1980). Nishiwaki and Sasao (1977) report what they believed was a displacement of Baird's beaked whales (Berardius bairdii) and minke whales from areas of heavy marine traffic off Japan. However, they base their conclusions on data from different types and numbers of vessels fishing for different periods of time, and there was little evidence of decline in catch per unit effort. Because so many variables changed during the period when their data were gathered, it is impossible to interpret their data.

Approach

The four main components of the planned disturbance research were studies of the reactions of bowheads to (1) close approach by boats, (2) overflights by aircraft, (3) underwater seismic exploration activities, and (4) other industrial activities (e.g., dredging and drilling). Field work during both years was conducted in the eastern Beaufort Sea--a part of the Arctic Ocean--in August and the first half of September. Bowheads are more easily studied in those circumstances than at most other times, but even then the logistical difficulties are considerable. Most observations of bowhead behavior were made from an aircraft circling above the whales, often far offshore, but some were made by shore-based observers at Herschel Island, Y.T., and others from boats that we were using as disturbing objects or for other purposes.

Reactions to boats were examined experimentally by observing the behavior of bowheads before, during and after close approach by boats. These data were collected by observers in an aircraft circling high above the whales and by observers on the disturbing boat itself. Additional information was collected when aerial observers encountered bowheads near boats that were not under our control.

Reactions to aircraft were examined opportunistically during our complementary study of the normal behavior of bowheads (see 'Normal Behavior' section, Würsig et al. 1982). In addition, we carried out two brief experiments consisting of a period of observation at an altitude of 610 m, followed by periods at 457 m and/or 305 m, and we compared behavioral data collected from the aircraft and from shore.

Reactions to waterborne noise were to be studied by underwater playback techniques from shore or from a boat as opportunities allowed. In 1980, there were no opportunities, and in 1981 we used the limited number of opportunities to test the response of bowheads to an airgun deployed from our boat. (Arrays of airguns are one of the energy sources used in seismic exploration.) However, considerable information was obtained about the presence and behavior of bowheads near noisy industrial operations--seismic exploration, artificial island construction, drillships, and supply boats. The observations of whales near ongoing, full-scale industrial operations had the advantage of realism (in terms of both magnitude and duration), which we could not achieve otherwise, but interpretation is hindered by the lack of experimental control, including the lack of pre- and post-disturbance observations. For this reason, playbacks and related experimental work are a top priority for any future studies.

To assist in the interpretation of our observations on the presence and behavior of bowheads near boats, aircraft and various industrial operations, we recorded and analyzed the waterborne sounds from such sources. Whenever possible, such sounds were recorded near whales that were close to a source of potential disturbance. Thus we obtained information about the sounds being received by some of the whales that were observed. Our analyses of industrial sounds were conducted primarily because site-specific information was needed to interpret our data on disturbance responses. These sounds are described and analyzed in the 'Industrial Noise' section (Greene 1982).

METHODS

Situations when whales were observed near various sources of potential disturbance differed, and the exact procedure for recording these observations varied correspondingly.

Aerial Observation Procedures

We made aerial observations from a Britten-Norman Islander (BN 2A-21 model), based at Tuktoyaktuk. The Islander has two piston engines (Lycoming IO-540 series), a high-wing configuration (affording good visibility), and a low stall speed (affording good maneuverability). The dimensions of the Islander are wingspan 16 m, length 11 m, and gross weight about 3000 kg. The Islander that we used was equipped with a forward-looking radar that was used to measure distances to objects, a radar altimeter, and a VLF/Omega navigation system for accurate position-finding in the absence of landmarks. Sonobuoys could be deployed and monitored from the aircraft in order to record waterborne sounds.

Most observations were from altitudes of 457 or 610 m. This was high enough to avoid disturbing the whales significantly and to offer a good vantage point, and low enough to enable us to see clearly the behaviors of the animals. The usual procedure was to circle above the whales and observe certain behaviors. These included orientations with respect to true north (in the absence of disturbance) or with respect to the disturbance source (e.g. boat) when it was near the whales. The length of time at the surface, number of blows (respirations) per surfacing, intervals between blows, inter-animal distances, and relative speed of movement were also recorded. Orientations, inter-animal distances, interactions, and general activities were recorded at approximately 1-min intervals. When distinctively marked animals were seen, it was often possible to record durations of dives as well.

The aircraft crew consisted of a pilot and three or four observers. One observer (in the co-pilot's seat) used binoculars to follow closely the behavior of up to three or four 'focal' animals, while a second observer in the second seat on the right recorded behaviors on a broader scale. The observer who used binoculars had the best opportunity to record respirations and details of individual behavior. The other observer was better able to record relative positions and distances, orientations and social interactions. One or two additional observers in rear seats were responsible for deployment of sonobuoys, operation of audio recorders, videotaping of whale behavior, record keeping, operation of the radar (to measure distances to boats, islands, etc.), and supplementary visual observations. It was not possible to conduct disturbance experiments in a 'blind' or 'double blind' manner. Observers in the aircraft had to direct the operation of the boat and of the pilot. In any case, changes in aircraft altitude and (in most cases) activities of the boat were visually apparent to observers in the aircraft.

Whale behavior was videotaped intermittently in 1980 (when there usually were only three observers) and more regularly in 1981 (when there usually were four). A handheld color video camera (JVC-CV-0001) and portable videocassette recorder (Sony SLO-340) were used; the camera was directed through the side windows to record oblique views of bowheads. Videotapes were examined to corroborate and supplement the dictated description of whale behavior.

Boat Disturbance Experiments and Observations

Experiments with the 'Imperial Adgo'

During a four-day period in August 1980, we had an observer on a 16.1 m crew boat, the 'Imperial Adgo'. On 27 August 1980, we were able to use the boat for experimental disturbance trials involving a group of four whales off the Tuktoyaktuk Peninsula. During this period, aircraft-based observers who were in radio contact with persons on the boat directed boat maneuvers. A series of observations of whale behavior was made before, during, and after disturbance. A sonobuoy (AN/SSQ-41B) was deployed near the whales to monitor the boat noise to which they were exposed.

The 'Imperial Adgo' is a 16.1 m crew boat with twin General Motors diesel engines. These 8-cylinder engines are run at 2100 rpm for full speed, which is 22 kt (41 km/h). There is a 2:1 reduction gear box, and each propeller has three blades.

During systematic boat disturbance experiments and also at other times when bowheads were encountered by the 'Adgo', the LGL biologist on the boat estimated boat-whale distances and orientations of the whales visually. These two variables were recorded at each surfacing; it was not possible to follow individual whales from one surfacing to the next. The orientations of the whales in relation to the boat were recorded in the following way: A whale oriented directly away from the boat was said to be facing 12 o'clock; a whale oriented directly toward the boat was facing 6 o'clock; a whale oriented tangentially was facing 3 o'clock (if headed right) or 9 o'clock (if headed left); and so on (Fig. 2). In some analyses, whales oriented from 10 through 2 o'clock were considered to be facing away from the boat, those oriented from 4 through 8 o'clock were facing toward the boat, and those oriented toward 9 or 3 o'clock were 'neutral'. Where statistical tests were required, 'expected' values were weighted according to the proportion of a clock face represented in each category.

Opportunistic Observations of Reactions to Boats

On 19 August 1980, the reactions of a group of about 15 bowheads to a small ship, the 'Canmar Supplier IV', were observed from the aircraft. The airborne observers noticed that the ship was approaching the whales, and recorded whale orientations and behavior as the vessel approached from about 5 km away, passed through the group of whales, and then departed. The 'Supplier IV' is a 65 m, 1270 long ton vessel with two main engines totalling 7200 shp; normal running speed is 26 km/h.

Similarly, on 23 August 1981, while we were observing whales near the drillship 'Explorer II', we noticed that the seismic exploration vessel

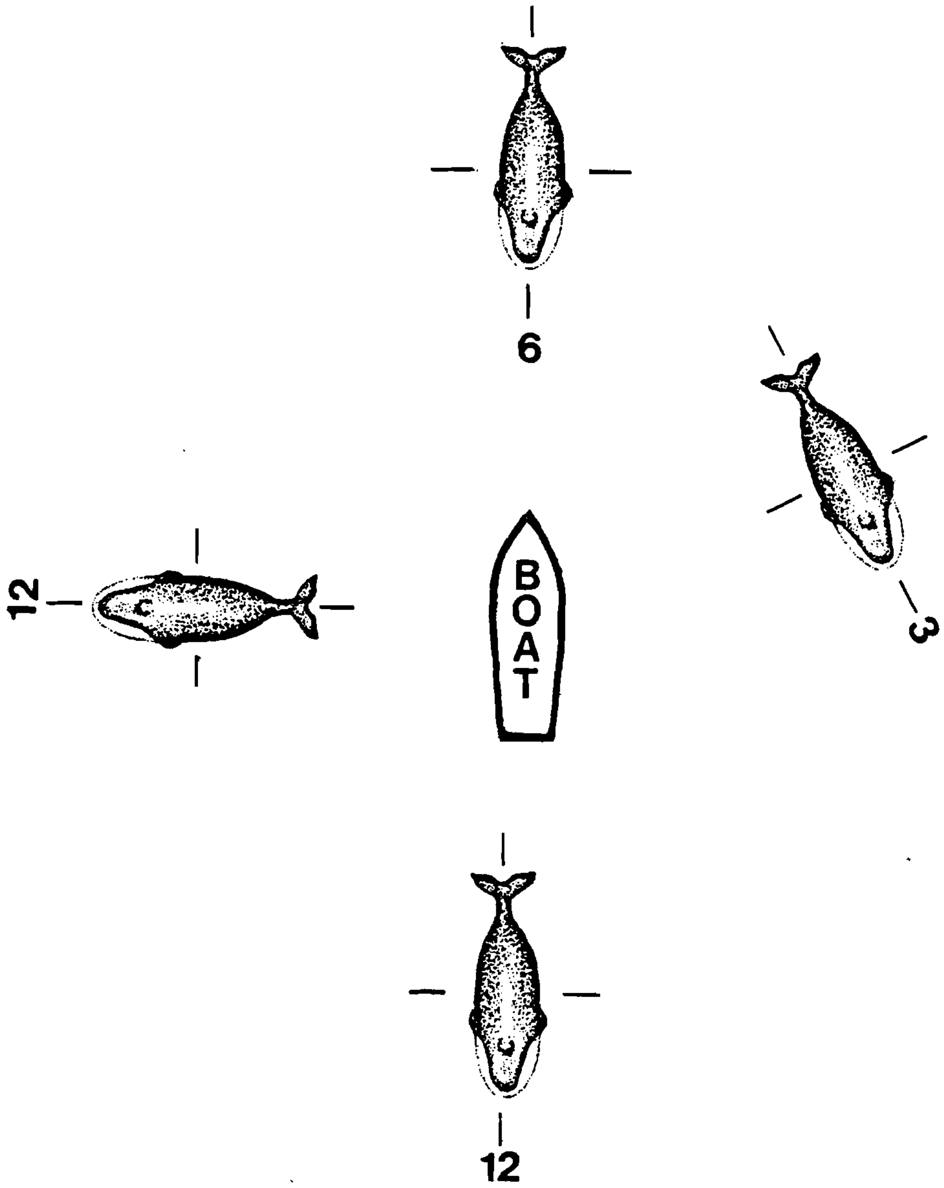

FIGURE 2. Examples of orientations of whales with respect to the boat.

'Arctic Surveyor' was passing through another group of whales. We diverted briefly (20:29 to 20:40 MDT) to observe the behavior of these whales. The vessel was travelling and was not 'shooting' seismic impulses at this time.

On 25 August 1981, we obtained information about the incremental effect of close approach by a boat when seismic noise was already present in the water. After observing the behavior of bowheads about 6-8 km from the 'Arctic Surveyor', we directed our chartered boat, the 'Sequel', to pass close to the whales. 'Sequel' is a 12.5 m former fishing boat with one 115 hp diesel engine (GM 471) and cruising speed 14 km/h. Bowhead behavior was observed from the aircraft before, during and after the approach by 'Sequel'. Seismic noise was present in the water throughout this period.

Aircraft Disturbance Experiments and Observations

In 1980, observations of disturbance of bowheads by aircraft were limited to those obtained during aerial studies of normal behavior. During these studies, we believe that our Islander aircraft (described above) sometimes disturbed whales. When apparent disturbance took place, we recorded the circumstances and behavior of the whales. In particular, we noted whether the whales dove immediately after the aircraft arrived overhead. Similar observations were made in 1981.

Although most observations were from a height of 457 m (1500 ft), some were from lower altitudes when the cloud ceiling was low, and others were from higher altitudes--usually 610 m (2000 ft)--when whales seemed especially sensitive to the aircraft. We have summarized the dive, surfacing and respiration characteristics that were recorded while the aircraft was at different altitudes. In addition, on two occasions in September 1981, we made an initial series of observations of a group from 610 m, and then descended to 457 m and/or 305 m for additional observations. Dive, surfacing and respiration characteristics during the periods at the various altitudes were compared.

On 3 September 1981, whales near Herschel Island, Y.T., were observed simultaneously from the Islander aircraft and from a cliff-top observation post on the island. (Würsig et al. [1982] describe the shore-based component of the study.) Observations from Herschel Island before and during this period of aircraft observation were compared to determine whether arrival of the aircraft affected the whales.

We also recorded the waterborne sound from our Islander observation aircraft as well as a Twin Otter and a Bell 212 helicopter. In each case, the aircraft flew several passes at 153-610 m ASL over a hydrophone or sonobuoy. Results appear in the 'Industrial Noise' section (Greene 1982).

Bowhead Behavior Near Seismic Exploration

Opportunistic Observations near a Seismic Ship

On 21 August 1980, a seismic exploration vessel, the 'Arctic Surveyor', was discharging a sleeve exploder system in an area about 13 km (7 n.mi.) from seven bowheads. This occurred late in the day when the light was failing, but we obtained some data on surface times, intervals between blows, and blows/surfacing. Observations before and after the incident were not possible, but behavioral data gathered near the seismic vessel can be compared with data gathered in the same general area on 20 and 22 August in the absence of apparent disturbance. Limited information about seismic sounds in the water near the whales was also obtained with a sonobuoy.

Similarly, on 25 August 1981 we again observed whales as close as 6-8 km from the 'Arctic Surveyor'. Part way through the observation session, we directed our chartered boat, the 'Sequel', to pass close by these whales. Thus we obtained data on behavior in the presence of a boat plus seismic noise as well as with seismic noise alone.

Airgun Experiments, 18-19 August 1981

Controlled experiments with a full-scale seismic ship were not possible, but we used a single 40 in^3 (655 cm^3) Bolt airgun from our chartered boat in August 1981. According to the manufacturer, the source level of this airgun is 222 dB//1 μPa at 1 m when it is at a depth of 9 m, and slightly less when at a depth of 6 m as in our experiments. When airguns are used for full-scale seismic exploration, an array of guns totalling about 1400-2000 in^3 is used; some guns in the array are smaller than 40 in^3, and others are larger. The source level of such an airgun array is roughly 248 dB//1 μPa at 1 m (Johnston and Cain 1981). Sound levels reaching the whales from our one airgun at a distance of 5 km were at least as high as those that would reach whales 24 km from the 'Arctic Surveyor' (Greene 1982).

Each airgun experiment consisted of a pre-airgun control period, an airgun discharge period, and a post-airgun period. Throughout all three periods, the Islander observation aircraft circled overhead and the 'Sequel' moved slowly (5.6 km/h) in a large circle at a more or less constant distance from the whales. This distance was maintained by directions from the aircraft, which could measure the distance to the 'Sequel' by radar. During the airgun-discharge period, the airgun was discharged every 10 s for 19-20 min.

The airgun was operated from compressed air tanks that had been filled to 3000 psi before the pre-airgun control period began. Thus there was no compressor noise during the experiments. By the end of the 19-20 min discharge period, the available air pressure had decreased to about 500 psi, and the intensity of the waterborne impulses had decreased. Sounds near the whales were monitored throughout each experiment via sonobuoys.

Our permit under the Marine Mammal Protection Act and the Endangered Species Act specified that we first carry out an experiment at a distance of 5 km. If there was no major response at that distance, we were permitted to approach to 2 km. The first experiment (18 August) was carried out 5 km from echelon-feeding whales. Because we observed no major response (the whales continued to feed), the second experiment (19 August) was carried out at about 3 km. We had hoped to replicate the experiment several times; however, there were no additional suitable opportunities. A group of whales that we had hoped to work with on 24 August proved to contain three calves, and our permit obligated us to avoid experimenting with calves. Whales that we had hoped to work with on 25 August were within an area ensonified by the seismic vessel 'Arctic Surveyor'. No other potentially suitable situations were available to us.

Bowhead Distribution Near an Artificial Island

During the 1980 open-water season, Esso built up and improved its Issungnak artificial island. The major activity at the site was dredging by the 'Beaver Mackenzie' of material from the adjacent sea bottom for the island. The suction dredge 'Beaver Mackenzie' is an 86.5 m vessel with a gross tonnage of about 2200 (detailed description in Greene 1982). The sounds of the island construction operation were studied in detail (Greene 1982).

To study the distribution and relative abundance of bowheads near construction activities at Issungnak artificial island, we flew systematic surveys near the island on 9, 11, 12, and 22 August 1980. There were 16 survey lines, each 33.3 km long, spaced (in theory) at 3.2 km intervals; Issungnak was at the center of the survey area (Fig. 1). (Because of navigational difficulties the lines were not as straight or as evenly spaced as planned or desired.) To ensure that the whales would not be disturbed by our aircraft, we flew at 610 m ASL. Airspeed was 185 km/h. Two observers were used, one in the right-front (co-pilot's) seat and the other in a left seat at the back of the aircraft. Transect width was 1.6 km, 0.8 km on each side of the flight track. Thus about 50% of the 33 x 51 km area was surveyed during each flight (except when fog precluded complete coverage).

We recorded the locations and numbers of whales, the presence of calves, and the whales' orientation and general behavior. All sightings were classified as 'on-transect' or 'off-transect'. Because our primary objective was to document bowhead distribution in relation to distance and direction from the source of potential disturbance at Issungnak, we rarely interrupted these surveys to circle and observe the behavior of the whales.

Another LGL survey team also covered the Issungnak area in 1980 during studies for Esso Resources Canada Ltd. Their survey lines, which were also oriented north-south, extended for about 35.4 km north from 69°47.5' N latitude; thus the north ends of these lines were about 8 km north of Issungnak. The lines were spaced at 3.2 km intervals, with 6 lines west and 6 lines east of Issungnak. These surveys were at 305 m ASL and airspeed 262 km/h (Fraker and Fraker 1981).

Because of the higher altitude and lower airspeed during surveys for the present study, we would have had any given point in view for a longer time than would the observers doing the Esso surveys.

In 1981, bowheads were not present near any industry activity long enough to warrant the above kind of systematic survey coverage.

Presence of Bowheads Near a Drillship

On 23 August 1981 we discovered two groups of whales near the drillship 'Explorer II' (about 15 km and 4 km away). We observed the first group from 18:17 to 19:11 MDT, and the second group from 19:17 to 21:20, except from 20:29 to 20:40 when we interrupted these observations to record the response of another group of whales to the passage of a vessel. We observed from an altitude of 610 m, and recorded the usual information about respiration, surface and dive times, and general activities. Drillship sounds reaching the whales were recorded via sonobuoys, and drillship sounds in general were also studied in more detail from the 'Sequel' (Greene 1982).

Sightings by Industry and Other Personnel

Many people working offshore in the Beaufort Sea region see whales in the course of their work. These sightings provide information about the seasonal distribution of whales, their directions of movement, and their presence near various sources of potential disturbance. To make it possible for people working on projects for industry, government, and universities to record their observations systematically, we distributed business-reply cards with spaces for species, location, date, the vessel or island from which the observation was made, and the name and address of the observer.

Recording and Analysis of Waterborne Industrial Sounds

Two sound recording systems were used in each year: a boat system employing hydrophones, and an airborne system employing sonobuoys that transmit the waterborne sounds to the aircraft. Both systems are described in the 'Industrial Noise' section (Greene 1982).

RESULTS

Reactions of Bowheads to Boats

The observations of bowheads' reactions to boats involved four different vessels. The 'Imperial Adgo' was a fast, 16.1 m, diesel-powered crew boat; we observed from it on three days when it was involved in other work and on one day when it was under our control. The 'Sequel' was a slow, diesel-powered, 12 m fishing boat that we chartered in 1981. Observations near two larger vessels, 'Canmar Supplier IV' and the 'Arctic Surveyor' (not shooting its seismic devices), were made during chance opportunities.

Boat-based Observations, 'Imperial Adgo'

We observed the behavior of bowheads from the boat 'Imperial Adgo' on 23, 24, 26 and 27 August 1980; fog and rain precluded work on the 25th. On 27 August we used the 'Adgo' and the observation aircraft in a coordinated way to carry out experimental disturbance of bowheads. The data collected from the boat during this experiment are included here; the data collected from the aircraft on 27 August are presented in the next section. The underwater sound of the boat was recorded via a sonobuoy and these results are presented in Greene (1982). The weather during the four working days was generally favorable. The light winds (5-9 km/h) resulted in sea states of 1 and 2.

Figure 3 shows the orientations of whales recorded from the 'Imperial Adgo' (see Appendix 1 for detailed data). It was easier to record orientations of whales that were near ($\leq$900 m) the boat than those of whales that were distant (>900 m). Therefore, the majority of the data concern bowheads in the nearer category. The whales did not orient in all directions with equal frequency, regardless of whether the 'Adgo' was cruising or stopped in the water with its engines off or idling (Table 1A).

Although whales did not orient uniformly when the engines were off, the frequency distribution approached uniform more closely under this condition then when the engines were idling or engaged (Fig. 3). The deviation from uniform was not statistically significant when the range was greater than 900 m (chi-square 5.06; df = 2; $0.05<p<0.10$), but was significant when the range

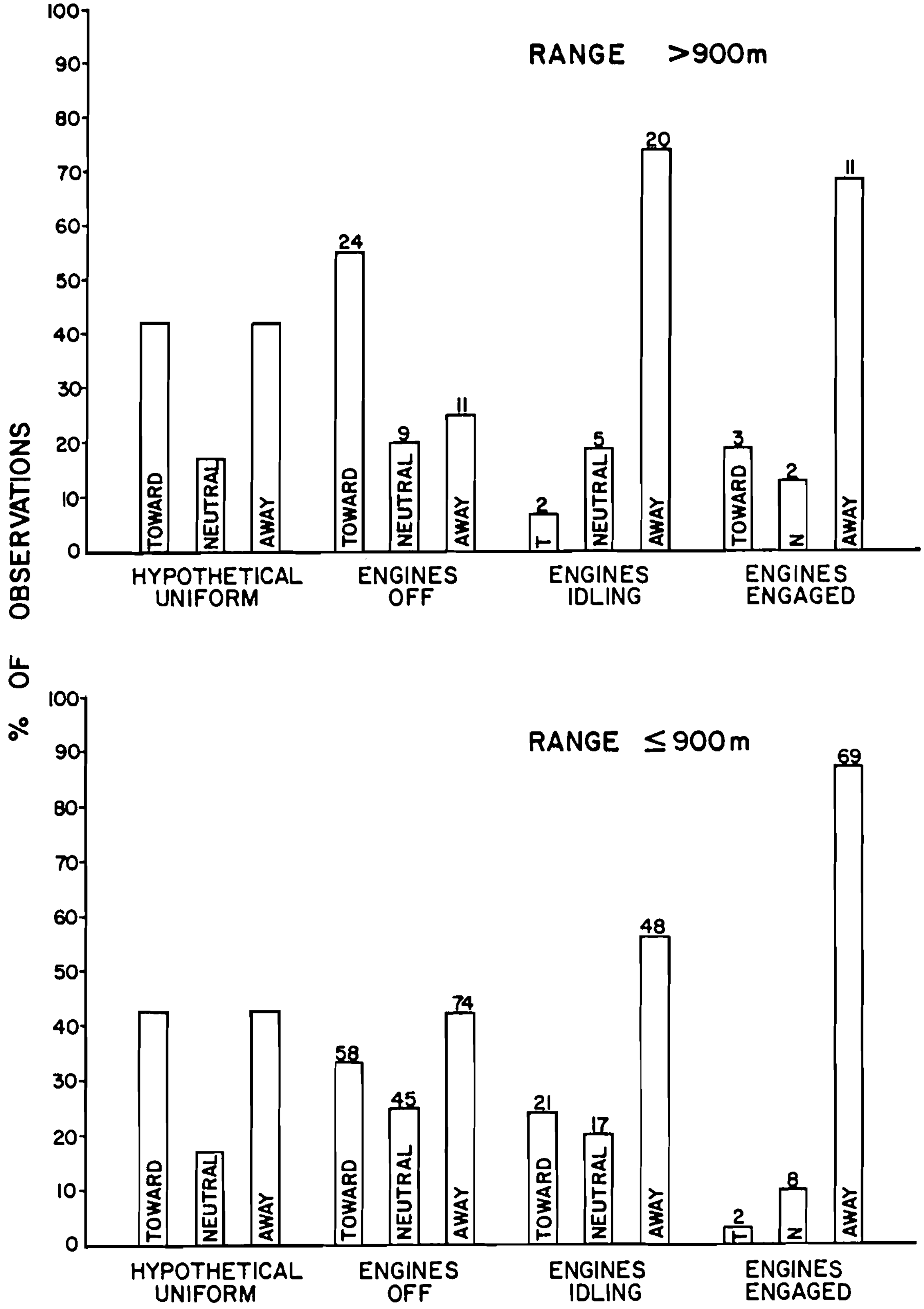

FIGURE 3. Orientations (with respect to boat) of bowhead whales observed from the 'Imperial Adgo' when it was (1) stationary with engines off, (2) stationary with engines idling, and (3) cruising near whales. The hypothetical orientations are those that one would expect if the whales were randomly oriented. See 'Methods' for explanation of categories. Numbers above bars are sample sizes.

Table 1. Summary of chi-square tests applied to orientations of bowheads recorded from the boat 'Imperial Adgo' on 23, 24, 26 and 27 August 1980. See Appendix 1 for data and text for explanation of categories.

Boat Engine Condition	Chi-Square	df	P
A. Were bowheads oriented uniformly in all directions?			
Off	28.67	6	<0.001
Idling	37.53	6	<0.001
Engaged	152.58	6	<<0.001
B. Were orientations similar in the following conditions:			
Off vs. Idling	19.48	6	<0.01
Off vs. Engaged	66.84	6	<<0.001
Idling vs. Engaged	22.26	6	<0.005
C. Were orientations of bowheads $\leq$900 m and >900 m from the boat similar?			
Off	8.89	5*	>0.1
Idling	14.16	4*	<0.01
Engaged	6.89	2*	<0.05

* Adjacent categories summed to eliminate low-frequency cells.

was 900 m or less (chi-square = 11.51; df = 2; $p<0.005$). In the latter case, the number of whales oriented away from the boat was the same as expected, so the significant chi-square was attributable to the 'toward' and 'neutral' categories.

The orientations differed from uniform in a highly significant way when the boat was moving (engines engaged) and to a lesser degree when the engines were only idling (Fig. 3, Table 1A). The orientations were statistically different under the different conditions (Table 1B). Predictably, the greatest difference was between the engines 'off' and 'engaged' conditions. The orientations tended to be away from the boat when it was idling and especially when it was moving. The orientations taken by the whales were also related to the distance from the boat, except when the engines were off (Table 1C). When the engines were idling, the whales that were beyond 900 m tended to orient away from the boat more strongly than did those within 900 m; however, the sample size in the former category is relatively small. When the engines were engaged, the whales in both distance categories tended to orient away from the boat, but the close whales did so more strongly.

On one occasion in August 1980 while the 'Imperial Adgo' was travelling at full speed (41 km/h), the boat nearly collided with a bowhead calf. Two experienced whale observers were actively looking for bowheads at the time, and even so the boat came very close to the calf before it was seen. This incident indicates that bowheads, or at least bowhead calves, sometimes may be incapable of avoiding high-speed crew boats. It further indicates that the boat crew may not always see the whale in time to avoid it.

In summary, bowheads observed from the 'Imperial Adgo' showed a strong tendency to orient away from the boat when it was moving within 900 m. There was a similar but less intense response when the distance between the boat and the whales was >900 m, or when the boat was stationary with its engines idling. Although the pattern of orientations when the boat was stationary with its engines off was not statistically uniform, similar overall numbers of whales were oriented toward and away from the boat in that situation. Although we did not contact any whales with a boat, one 'near-miss' incident involving a bowhead calf and a high-speed crew boat indicates that collisions are possible.

Boat Disturbance Experiment, 'Imperial Adgo'

On 27 August 1980, by maintaining radio contact between boat and aircraft, we guided the 'Imperial Adgo' toward a group of bowhead whales, thus permitting a series of aerial observations before, during, and after the boat approached the whales. Observations were made from the Islander aircraft circling at 610-762 m. The experiments took place offshore of McKinley Bay, N.W.T., in water 17-19 m deep, sea state 1.

At 14:12, a group of four bowhead whales, more or less stationary, were observed about 3.7 km from the 'Adgo'. Two had their mouths open, briefly, but apparently were not skim feeding as whales in this area had been doing commonly a few days earlier. On 27 August, few whales remained in this area, where there had been scores recently (cf. Renaud and Davis 1981). Apparently the four animals that were the subjects in this experiment were among the last ones remaining in this area.

The disturbance trials were divided into four phases: pre-disturbance 'control', disturbance with boat idling, disturbance with boat at speed near whales, and post-disturbance (boat leaving area). Two series of disturbance trials were conducted. The following aspects of the whales' behavior lent themselves to observation and quantitative analysis: (1) time at the surface, (2) distance to nearest neighbor, (3) proportion of surfacings with only one blow, and (4) orientation with respect to the boat. It was not possible to recognize particular individuals by any distinctive markings, so dive times and movements of individuals from one surfacing to the next could not be assessed.

Pre-disturbance 'control' data were collected as the boat remained 3.7 km away from the whales with its engines off (Table 2). There were two periods when the boat stood-by several kilometres away with its engines idling: one was before the first pass by the boat through the group of whales, and the other was between the first and second passes by the boat. The post-disturbance period followed the second pass by the boat, when the boat left the area near the whales.

Table 2. Duration of various phases of the experimental disturbance of four bowhead whales by the boat 'Imperial Adgo' on 27 August 1980. See text for details.

Episode	Phase	Boat to Whales Distance (km)	Duration (min)
1	pre-disturbance (engines off)	4	28
2	disturbance (boat idling)	3-4	30
3	disturbance (boat at speed near whales)	0.5-4	8
4	disturbance (boat idling)	4-9	18
5	disturbance (boat at speed near whales)	0.1-4	9
6	post-disturbance (boat leaving area)	>4	20

Operations of the boat had a clear effect on the length of time that the whales remained at the surface. During the pre-disturbance 'control' period (episode 1 in Table 2) the whales stayed at the surface for longer periods that were of relatively constant duration, compared to whales that had been affected by the boat (Fig. 4A). The whales apparently responded to the boat's disengaged engines (episodes 2 and 4) by reducing their mean time at the surface from about 82 to 58 s; this difference was statistically significant ($t = 2.79$; $df = 31$, $p<0.01$). When the boat was operating close to the whales at cruising speed (episodes 3 and 5), the mean time at the surface dropped further and the variability increased. While the 'Adgo' was within approximately 1 km of the whales, they actively tried to avoid the boat. After the boat left (episode 6), the mean surface time increased, but the times remained more variable than before disturbance. The difference between the pre-disturbance 'control' surface times and those seen when the boat passed near the whales was highly significant ($t = 4.47$, $df = 21$, $p<0.001$); the means during the control period were less strikingly different from those as the boat left ($t = 2.67$, $df = 19$, $p<0.02$).

The reduction in time at the surface during disturbance was also reflected in a reduction in the number of blows per surfacing. During 18

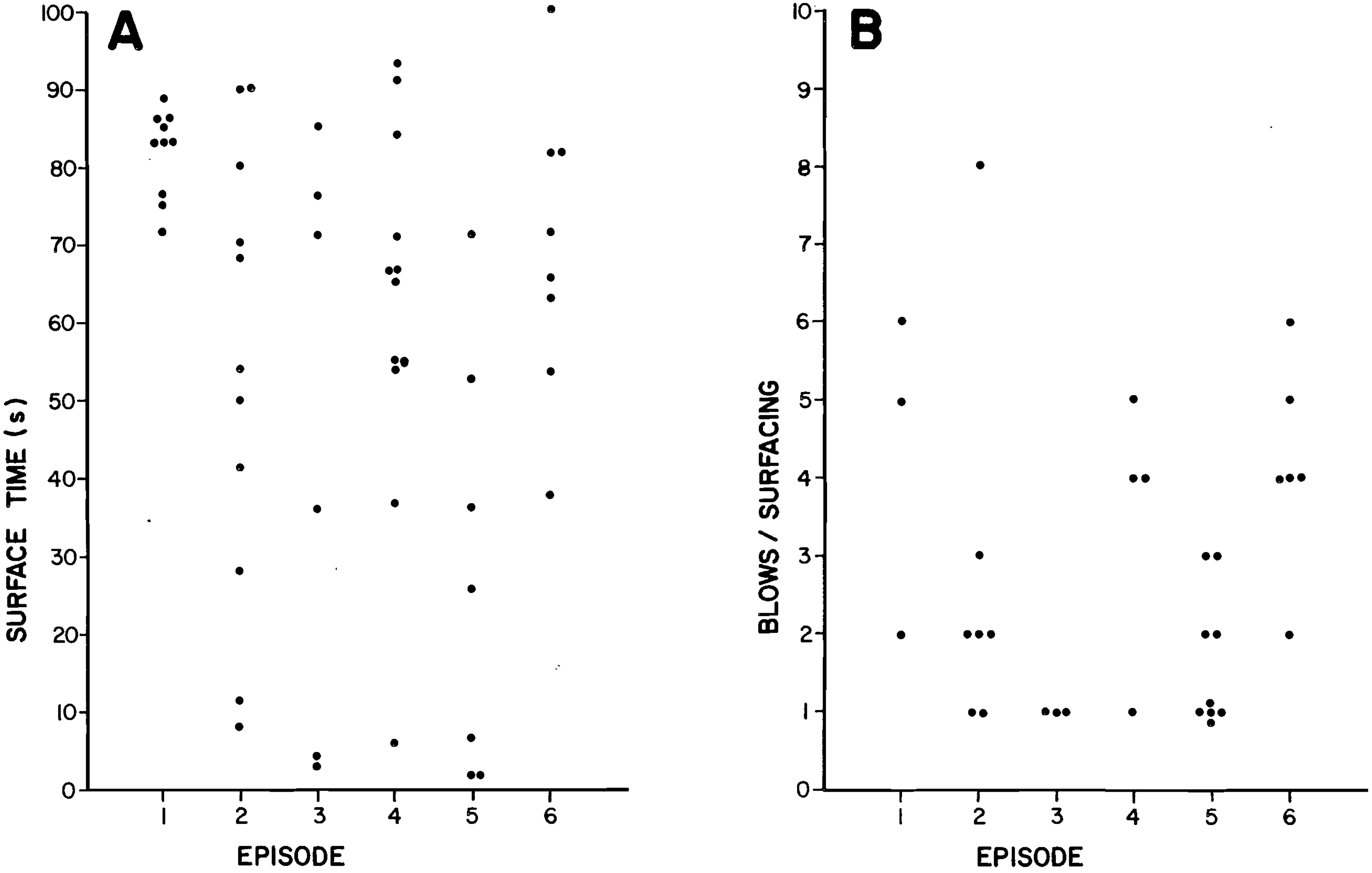

FIGURE 4. Surface times per surfacing and blows per surfacing during different episodes in the boat disturbance experiment on 27 August 1980. Detailed observations of blows/surfacing were not possible in each case; therefore, Fig. 4B shows fewer events then does Table 3. See text and Table 2 for explanation of episodes.

surfacings before or following disturbance, the whales always blew more than once before diving again (episodes 1 and 6, Table 3). However, during 38 surfacings when the boat was either idling or running near the whales, the whales blew more than once during only 27 (71%) of the surfacings (episodes 2-5, Table 3). The difference between the two percentages is significant (chi-square = 6.48, df = 1, $p<0.025$).

Table 3. Frequency of surfacings with 1 and >1 blow during boat ('Imperial Adgo') disturbance experiments on 27 August 1980*.

Episode	Experimental Condition	Number of Blows/Surfacing 1	>1	Total Surfacings
1	pre-disturbance (engines off)	0	9	9
2	disturbance (boat idling)	2	10	12
3	disturbance (boat at speed near whales)	3	3	6
4	disturbance (boat idling)	1	10	11
5	disturbance (boat at speed near whales)	5	4	9
6	post-disturbance (boat leaving area)	0	9	9
TOTALS		11	45	56

* It was possible to determine whether there was 1 or >1 blow/surfacing in more cases than it was possible to obtain the exact number of blows. Therefore, this table shows more events than does Fig. 4B.

Disturbance by the boat also resulted in the whales' spreading out more. During the pre-disturbance period, the mean of the estimated 'distance to nearest neighbor' values was 112 m (n = 7), but during and after disturbance (episodes 2-6), this increased to 562 m (n = 18, Fig. 5). A t-test applied to the nearest neighbor data (log transformed) shows that the difference was statistically significant (t = 4.97, df = 23, $p<0.001$).

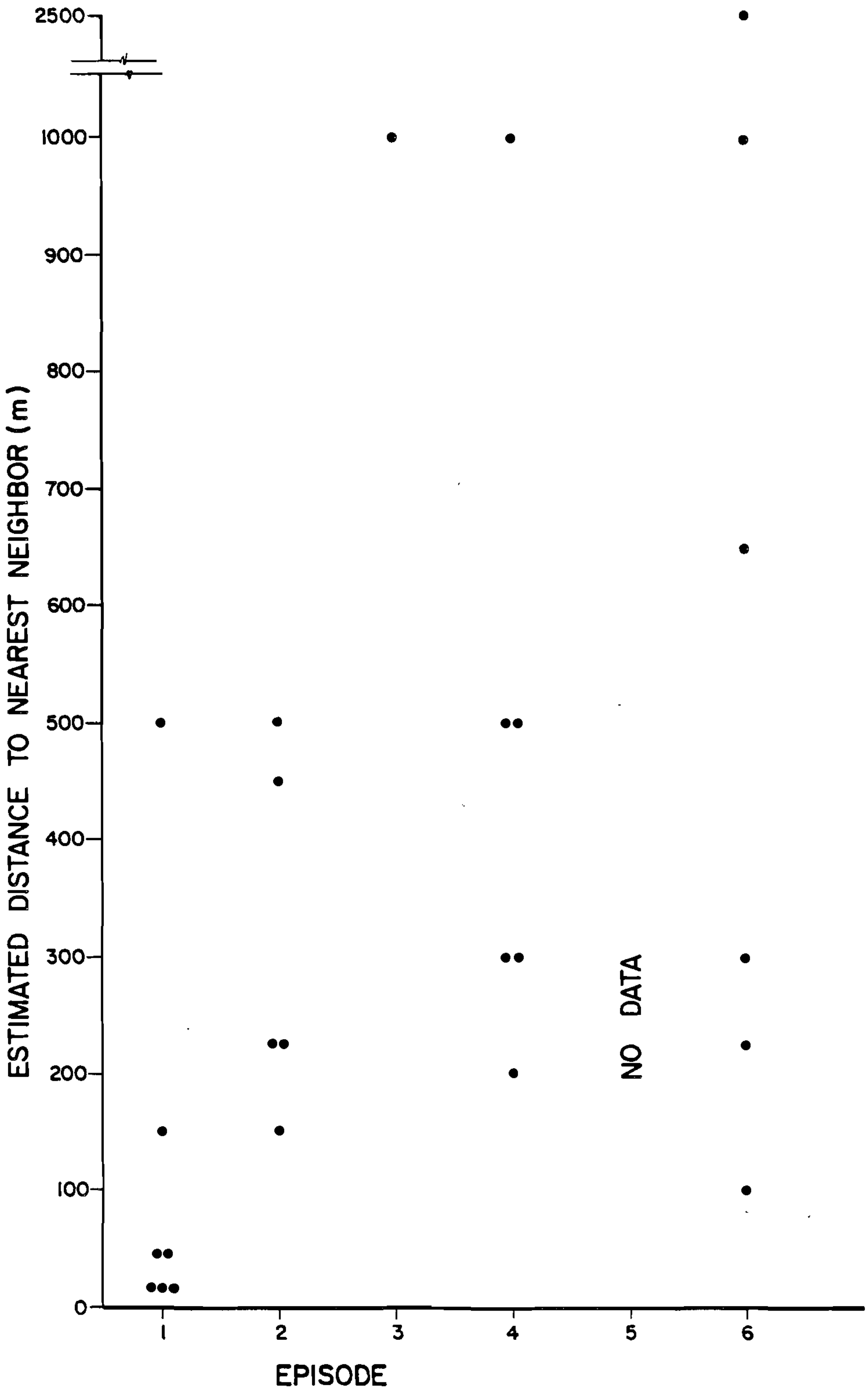

FIGURE 5. Estimated distance to nearest neighbor during different episodes of the boat disturbance experiments on 27 August 1980. See text and Table 2 for explanation of episodes.

(Distance to nearest neighbor was estimated at intervals of 1 min or more in an attempt to ensure that each observation was independent of the preceding observations.)

In summary, the group of four bowhead whales responded to the boat 'Imperial Adgo' by spending less time at the surface after each dive, and by scattering. The effect was apparent when the boat was 3-4 km away and stationary with its engines running. The effect was greater when the boat closely approached and passed the whales. During pre- and post-disturbance periods the whales blew more than once during each surfacing, but during disturbance trials the whales blew only once during 11 (29%) of the observed surfacings. The distance to the whales' nearest neighbors increased during the disturbance and remained greater during the observed post-disturbance period. However, after disturbance the time at the surface and number of blows per surfacing increased toward pre-disturbance levels, although both remained more variable.

Responses to a Ship, 'Canmar Supplier IV'

On 19 August 1980, at about 19:20 h, a group of about 15 bowheads was discovered about 18 km E of Pullen Island, in an area with a diameter of about 2.8-3.7 km, water depth 10-12 m, and near-calm winds. Our observations were made from the plane circling at an altitude of 610 m. The surface water was turbid throughout the area, but there was an interface separating a more turbid from a less turbid area. Most of the whales were in the more turbid part.

At 19:20 two boats about 6 km NE of the closest whales were observed moving southeastward, and another vessel, the 'Canmar Supplier IV', was located 4.6 km E of the whales and was headed directly toward the whales. The behavior of the whales in response to the latter vessel was observed.

The whales were diving and moving relatively quickly through the shallow water. The paths that they took were evident from the mud clouds that they created as the tail beats disturbed sediments from the bottom (see 'Normal Behavior' section). These whales may have been feeding. The whales appeared to be spread out more or less evenly with individuals separated from their nearest neighbors by about 15 body lengths (225 m). The animals frequently exhaled underwater.

The whales made no apparent effort to avoid the 'Supplier IV' until it was very close. When the boat approached to within about 800 m, the whales oriented away from it and appeared to try to out-swim it. As the boat came within about 300 m, the whales dove, all bringing their flukes clear of the water. Underwater exhalations also were observed during this time. Whales that were to the sides of the track taken by the boat tended to orient directly away from the boat as it came abeam of them. After the boat was past the whales by 800 m or more, they appeared to orient in a variety of directions, without respect to the boat track.

The orientations of animals at the surface were recorded at 1 min intervals as the boat approached and less frequently afterward (Table 4). A chi-square test for uniformity was applied to the observations. Because of the limited data, it was necessary to increase the number of observations per cell by reducing the number of directional categories from 8 to 4. To do this, the number of observations in each cardinal direction (N, E, S, W) was increased by one-half the number of observations in the two adjacent intermediate directions*. Before the boat passed through the whale concentrations, the orientations did not differ statistically from a uniform distribution (chi-square = 7.41, df = 3, $0.05<p<0.10$). After the vessel passed, the orientations did differ statistically from uniform (chi-square = 8.78, df = 3, $p<0.05$). Orientations before and after the disturbance were also statistically different from each other (chi-square = 8.34, df = 3, $p = 0.04$).

The observations were interrupted at 20:32, after 72 min, but resumed briefly at 23:24. At this time whales were still located near the muddy-clearer water interface and were apparently oriented randomly; poor light conditions made it impossible to collect quantitative data on orientations or inter-animal distances.

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* For example, to the number oriented N was added one-half of those oriented NW and NE, to the number oriented E was added one-half of those oriented NE and SE, and so on.

Table 4. Orientations of whales observed 18 km east of Pullen Island on 19 August 1980 before and after being disturbed by the 'Canmar Supplier IV'. During disturbance the vessel passed through the group of whales.

		Orientation							
Condition	Time	N	NE	E	SE	S	SW	W	NW
Before Disturbance	19:23-19:28	15	1	9	3	4	3	5	9
After Disturbance	19:54-20:13	14	3	4	3	20	3	10	6

In summary, on the evening of 19 August 1980, a group of about 15 bowheads (possibly feeding) were disturbed when a ship passed through their midst. They did not react overtly to the ship until it was within about 800 m. The initial response was to try to outrun it, and as it approached more closely, to scatter. Whales directly on the westbound ship's track responded by heading west; those to the sides moved away in other directions. However, the bowheads did not leave the area, and 3 h after the disturbance, bowheads (presumably the same ones) were still present in the area. Whatever the effect of the ship might have been, it apparently did not result in the animals leaving the area, at least in the short term.

Responses to a Ship, 'Arctic Surveyor'

During a brief period (20:29-20:40) on the evening of 23 August 1981, we observed the response of a group of at least seven whales among which passed the seismic vessel 'Arctic Surveyor'. Water depth was 23 m and the observation aircraft was at 610 m ASL. The vessel was travelling rapidly and was not shooting. (None of the equipment was lowered over the side, nor were 'shots' detected by either of the sonobuoys in the water at the time.) The vessel's speed at this time is unknown, but its cruise speed is 19.5 km/h. These observations were made about 11 km west of the drillship 'Explorer II'.

When we arrived, the furthest whales from the 'Surveyor' were a group of three approximately 2.8 km ahead of the boat; all were moving rapidly and were headed away from the boat. This was also true for the other whales, which were as close as 1 km but were to the side of the boat's track. During this encounter, the 'Surveyor' closed on some of the whales that were trying to outrun it. All but one changed course to move at right angles to the vessel's track as it closed to within approximately 400 m. The exceptional animal cut in front of the vessel, which passed within 100 m. Whales as far as 1.4 km behind the vessel continued to move away from the vessel's track.

Table 5 shows the surfacing and respiration characteristics that we were able to record. Clearly, the behavior of the whales near the 'Arctic Surveyor' was affected. Of the seven surfacings that we observed completely, there were two blows in one case and only one blow in the six others. The mean length of surfacing was only 11.0 s, and the mean length of dive was only 29.4 s. In contrast, average values for presumably undisturbed bowheads in water depths 16-30 m are 4.8 ± s.d. 2.93 blows per surfacing, surface time 70 ± 40.5 s, and dive time 245 ± 265 s (cf. Table 4 in 'Normal Behavior' section, Würsig et al. 1982). Thus, the whales were diving briefly and surfacing briefly while moving quickly away from the vessel.

Table 5. Surfacing, respiration and dive characteristics for whales observed near the ship 'Arctic Surveyor' on 23 August 1981.

Parameter	Mean	s.d.	Min	Max	n
Blow Intervals (s)	15	-	-	-	1
Length of Surfacing (s)	11.0	6.63	2	20	7
Blows/Surfacing	1.1	0.38	1	2	7
Length of Dive (s)	29.4	37.02	4	90	5

Responses to a Boat, 'Sequel'

After observing bowheads about 8 km from the active seismic vessel 'Arctic Surveyor' on 25 August 1981, we conducted a boat disturbance test using 'Sequel'. Water depth was 11 m. 'Sequel' approached a group of four whales at a speed of about 16.7 km/h, with the closest point of approach to the whales being approximately 300 m. Three of the four whales were socializing and playing with a log (see Würsig et al. 1982). The playing ended at 12:50:17, when 'Sequel' approached to within about 2.5 km. As it came to within about 2 km, all of the whales were moving rapidly away from 'Sequel', apparently trying to outrun the boat. As 'Sequel' closed on the whales, they changed course to move at right angles from the vessel's track. At 13:01:50, after 'Sequel' had passed the whales but still was within 1.5 km, the whales continued to move rapidly away from the vessel's track. By 13:09, the whales had stopped travelling and were milling; at this time, 'Sequel' was about 5.6 km from the whales and moving away from them at full speed. Throughout this period, the 'Arctic Surveyor', which was about 8 km east of the whales, was 'shooting' its sleeve exploders.

Figure 6 summarizes the surfacing and respiration characteristics for the whales under the influences of the 'Sequel' and 'Arctic Surveyor' (see Appendix 2 for detailed data). Blow intervals increased when 'Sequel' was near the whales ($F = 3.41$, df = 2,187, $0.025<p<0.05$). As expected, the length of time at the surface decreased when 'Sequel' came near the whales and then increased again afterward ($F = 4.09$, df = 2,69, $0.01<p<0.025$). The trend in number of blows/surfacing was consistent with that in surface times, i.e. both decreased under the influence of 'Sequel' and returned toward the pre-'Sequel' number afterward, but in the case of blows/surfacing the difference was only marginally significant ($F = 2.79$, df = 2,60, $0.1>p>0.05$). The dive times decreased dramatically when 'Sequel' was near the whales (Fig. 6), but the difference based on the small samples was not quite significant statistically (2-sided Mann-Whitney $U = 17$, $n = 8,9$, $0.05<p<0.1$).

These results show that even in the presence of continuous loud seismic noise, the approach of a small boat causes a pronounced flight response in bowheads.

Summary of Boat Disturbance Observations

In 1980, bowheads quickly moved away from the approaching boats after they came within 0.8 to 1.0 km. Initially the bowheads tried to outrun the approaching boats. When this failed, whales that were overtaken changed course to move perpendicularly away from the boat's track. The whales also spent a reduced amount of time at the surface and blew fewer times during

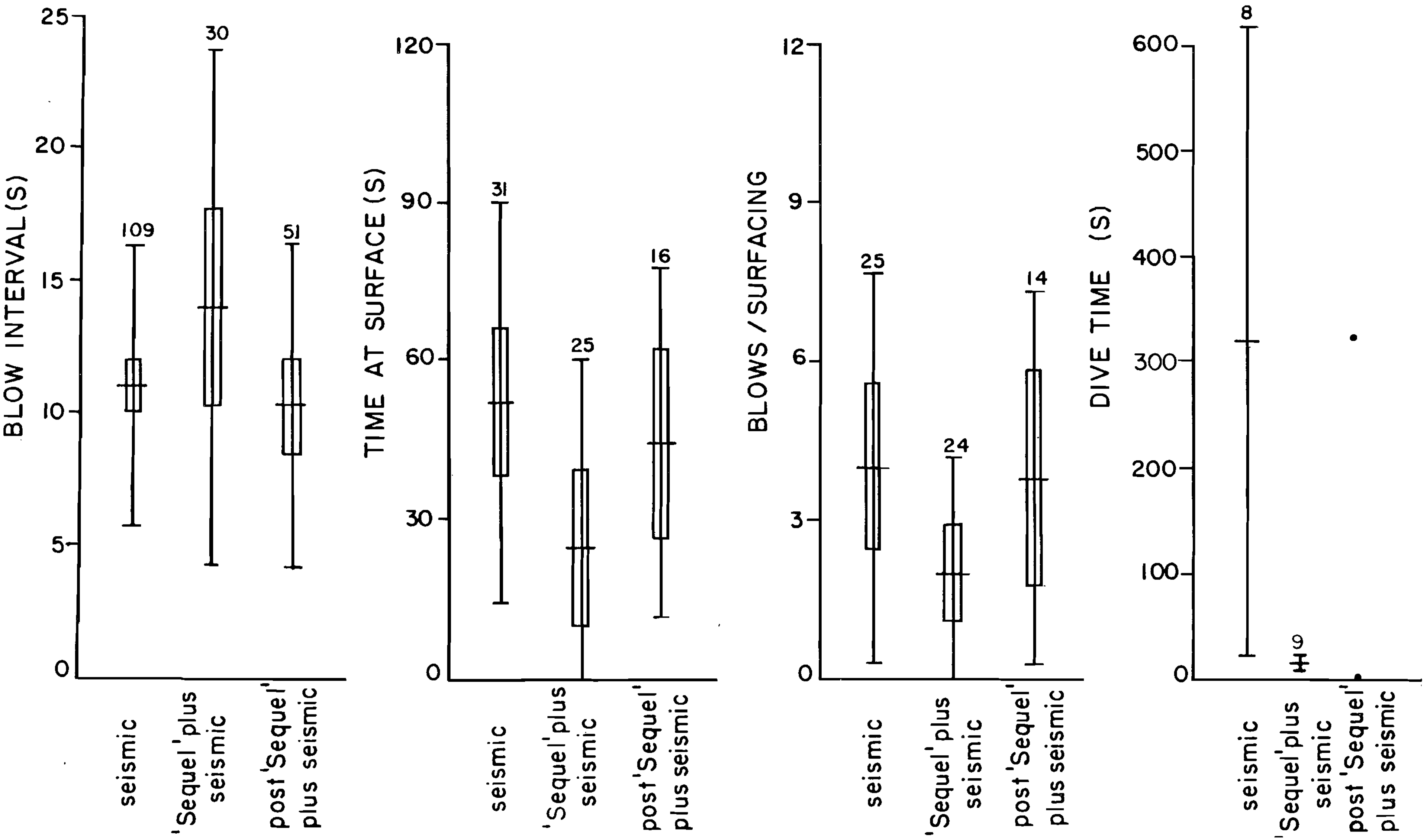


FIGURE 6. Surfacing, respiration and dive characteristics of whales observed near the seismic vessel 'Arctic Surveyor' before, during and after the boat 'Sequel' passed near the whales, 25 August 1981. The mean, ± 1 standard deviation (line), ± 95% confidence interval (rectangle), and sample size are shown. (No 95% confidence interval is shown for dive times, which were severely skewed.)

each surfacing; in some cases the whales blew only once. The disturbance caused the whales to become more widely separated. The whales did not continue to move away after the vessel passed, and disturbance apparently did not cause whales to vacate any specific areas. However, the increased inter-animal distances and any social disruption that this may have caused did persist for at least an hour, and possibly for several hours. The sound from a stationary boat, with engines idling but propellers disengaged, produced more subtle effects; whales tended to orient away from the boat and surface times were reduced.

In 1981, responses to the two vessel disturbance incidents that we observed were similar qualitatively to the responses in 1980. However, flight responses were noticed at a greater distance from the vessels than we observed in 1980 (up to 2.8 km vs. 1 km or less). The reasons for this seemingly greater sensitivity in 1981 are not known. Perhaps it was attributable to cumulative effects from multiple sources of potential disturbance. The 23 August 1981 boat disturbance event took place only 11 km from a drillship, and the 25 August event was only 8 km from an active seismic ship. Results from 25 August showed that bowheads reacted strongly to an approaching small (12 m) boat even when they were in an area ensonified by noise impulses from seismic exploration.

Reactions of Bowheads to Aircraft

We assigned a higher priority to studies of normal behavior, boat disturbance and disturbance from underwater sources of noise than we did to studies of aircraft disturbance. We did record cases of apparent disturbance owing to the presence of our aircraft during our observations of 'normal' (undisturbed) behavior, we compared all observations from 457 and 610 m, and we conducted two limited experiments involving observations from various altitudes. These observations were made as we circled above the whales in the Britten-Norman Islander (described in 'Methods'). We also compared blow intervals as observed from the aircraft and from land on the same day. Information about the amount and characteristics of aircraft noise transmitted into the water appears in the 'Industrial Noise' section (Greene 1982).

Occasions with Apparent Reactions

Table 6 lists instances when the observers in the aircraft believed that whales were being disturbed by the aircraft. The interpretation of the reactions as disturbance depended not only on the gross behavior, usually diving, but also on subtle behavioral differences. For example, when the whale(s) that had apparently been disturbed dove, it appeared that the dive was initiated as we approached and that the animal(s) went through the diving motions more quickly than usual.

Most whales that we believed were disturbed by our aircraft dove almost immediately (often without blowing) after we started to circle above them. Individuals that did blow before diving may have just surfaced from a previous dive. In one case (observation no. 10), a whale that had been moving in a straight line turned toward the aircraft as we approached; then it dove. In another case (observation no. 14), we had been circling above the whales observing their skim-feeding behavior from 457 m ASL. We descended from 457 m to 305 m in an attempt to make more detailed observations of skim feeding; as we descended the whales all dove, presumably in response to the aircraft.

In 1980, all observations of apparent disturbance occurred when the aircraft was at an altitude of 305 m or lower (Table 6), although on 22 August we observed skim-feeding whales from 305 m for about 30 min without apparently disrupting their activities. However, in 1981 the whales sometimes appeared to be disturbed when the aircraft was as high as 457 m (Table 6).

Comparison of Observations from Different Altitudes

In addition to the overt responses of the bowheads to possible disturbance by our aircraft, we have examined the surfacing and respiration characteristics of bowheads observed from different altitudes (Fig. 7; see Appendix 3 for detailed data). If the observation aircraft were a significant source of disturbance to the whales, one would expect this to be manifested to a greater degree at lower rather than higher altitudes; therefore, we compared observations made from 1500-1900 ft (457-580 m) with

Table 6. Instances of apparent disturbance of bowheads by the Britten-Norman Islander aircraft. See text for discussion.

Obs. No.	Date	Aircraft Altitude (m)	Whale Activity	Apparent Reaction to Aircraft
1.	4 August 1980	168	Water-column feeding	- dove almost immediately
2.	4 August 1980	213	"	- dove almost immediately; blew 1 time
3.	4 August 1980	213	"	- dove almost immediately
4.	4 August 1980	213	"	- dove almost immediately; blew 4 times
5.	4 August 1980	229	"	- dove almost immediately; blew 3 times
6.	4 August 1980	198	"	- 2 whales dove almost immediately
7.	6 August 1980	274	"	- dove almost immediately
8.	23 August 1980	305	Skim feeding	- dove almost immediately
9.	23 August 1980	305	"	- dove almost immediately
10.	23 August 1980	305	"	- changed course to head toward plane, then dove
11.	23 August 1980	305	"	- echelon of 3 whales dove as we descended from 457 to 305 m
12.	23 August 1980	305	"	- dove almost immediately
13.	23 August 1980	305	"	- dove almost immediately
14.	23 August 1980	305	"	- group of at least 5 skim-feeding whales dispersed
15.	27 August 1980	305	Unknown	- dove immediately
16.	27 August 1980	305	"	- dove immediately
17.	27 August 1980	305	"	- dove immediately
18.	31 July 1981	457	"	- dove almost immediately as plane circled
19.	1 August 1981	457	"	- 3 whales dove almost immediately
20.	1 August 1981	194	"	- changed orientation
21.	4 August 1981	457	"	- dove almost immediately

others made from 2000-2800 ft (610-854 m). Most observations in the former range were from 457 m; most in the latter range were from 610 m. We have used data only from observation periods when the whales were presumed to be undisturbed (except possibly by the aircraft).

Considering both years together, there were few clear differences in the surfacing and respiration characteristics recorded from the two altitudes (Fig. 7). The interval between blows was not significantly different for either year individually or for both years pooled. The same was true of the mean number of blows per surfacing. Although the mean times at the surface per surfacing were similar during observations from the two altitudes in 1980, the surface times tended to be longer when observed from high altitudes in 1981 (means 68.8 vs. 55.0 s, $t = 2.27$, $0.02<p<0.05$) and in the two years pooled (70.8 vs. 59.0 s, $t = 2.23$, $0.02<p<0.05$). Dive times were highly variable when observed from either altitude, and overall mean dive times for the two altitude ranges were almost identical (Fig. 7).

On two dates we circled one group of whales at high altitude (610 m) and then at one or two lower altitudes to determine whether their behavior would change when the aircraft descended. On 6 September 1981 we attempted a limited experiment to determine the response of whales to the Islander aircraft flown at altitudes of 610, 457, and 305 m. Unfortunately, the sea state was Beaufort 5; thus ambient noise was quite high, presumably masking much of the aircraft noise. The rough seas also made observations of the whales difficult. Another experiment was attempted on 8 September 1981. On that day, the sea state was Beaufort 1-2, but fog precluded work until late in the day when light conditions were deteriorating. Observations on 8 September were made from 610 m and 305 m.

The data on both 6 and 8 September show a trend toward decreased blow interval with decreasing altitude of the observation aircraft (Fig. 8 and Appendix 4). This difference was statistically significant for both 6 September ($F = 3.57$; df = 2,123; $0.05>p>0.025$) and 8 September ($t = 2.49$, df = 146, $p<0.02$). The data provide some suggestion that the same pattern might obtain for number of blows/surfacing and surface times (Fig. 8); however, there are too few data and the variances are too great for any

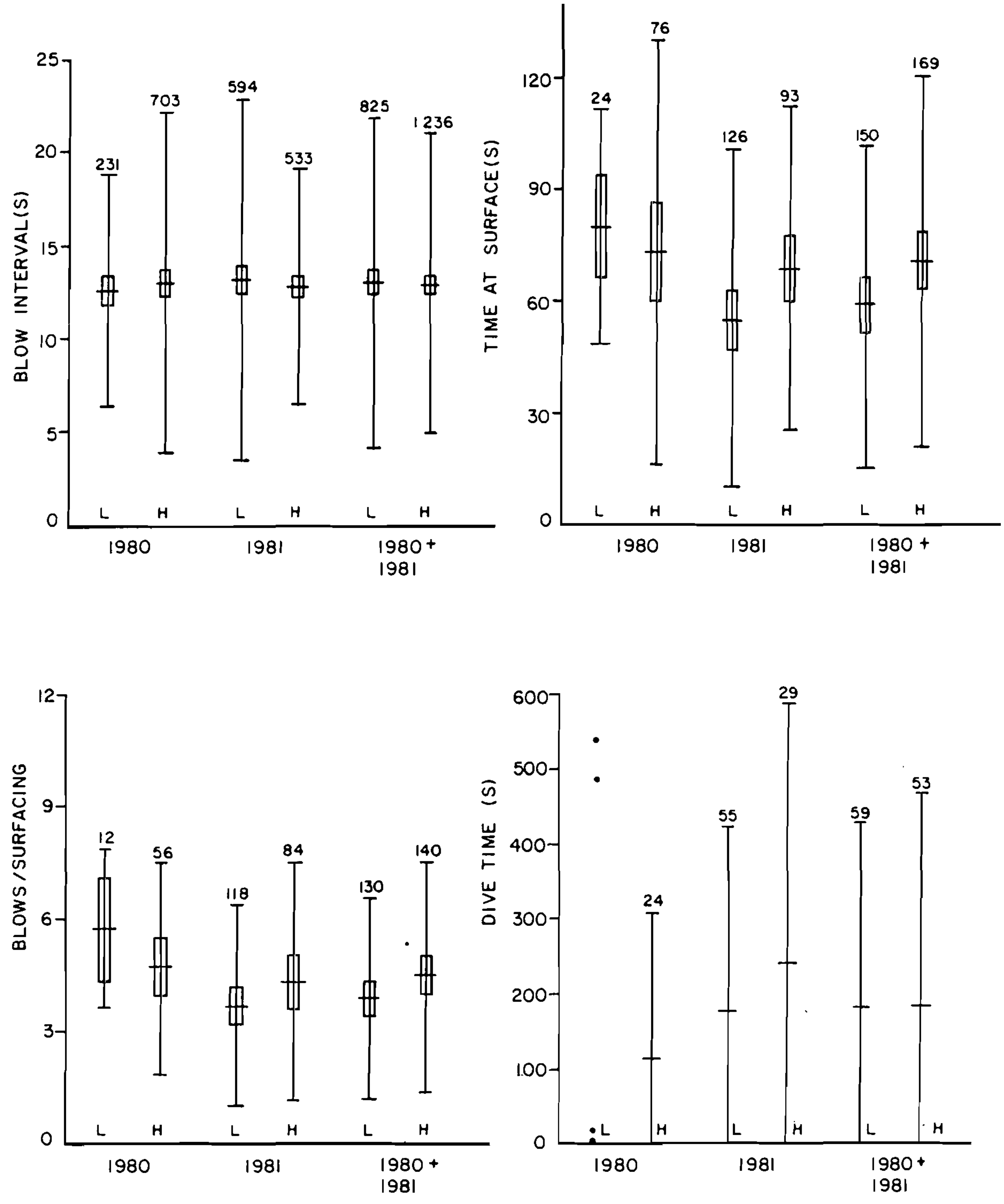


FIGURE 7. Surfacing, respiration and dive characteristics of bowheads observed from the Britten-Norman Islander aircraft at altitudes 1500-1900 ft (Low) and 2000-2800 ft (High) during 1980-1981. Only observations under presumably undisturbed (except possibly by the aircraft) conditions are considered. Presentation as in Fig. 6.

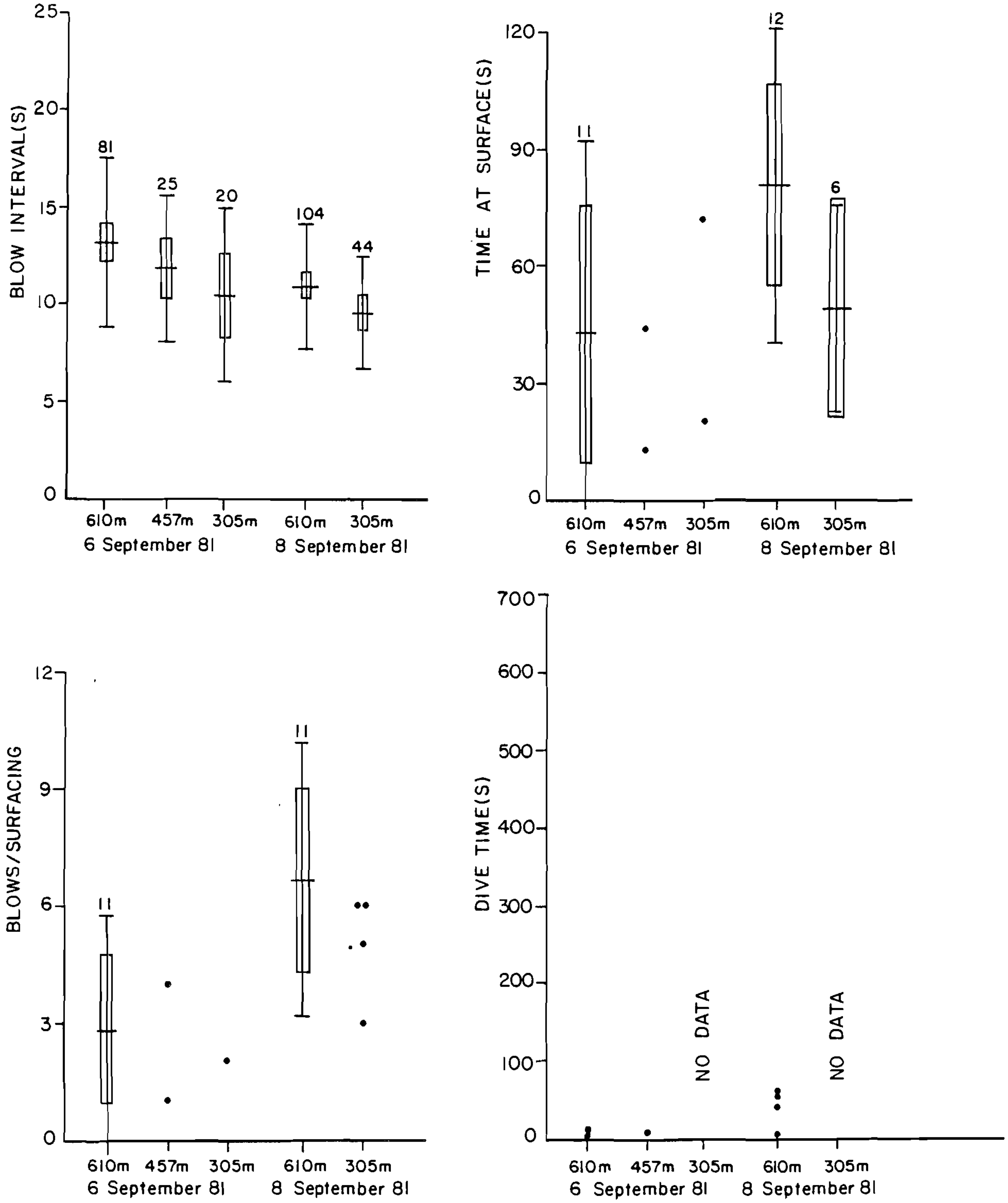


FIGURE 8. Surfacing, respiration and dive characteristics of bowheads observed from the Britten-Norman Islander aircraft at different altitudes on 6 and 8 September 1981. Presentation as in Fig. 6.

rigorous analysis. There are too few data on dive times to say anything meaningful.

Comparison of Observations from Aircraft and Shore

On 3 September 1981 we observed whale behavior near Herschel Island simultaneously from shore and the Islander aircraft. The weather was less than ideal--there were occasional snow squalls, although the winds were light. The ceiling was only 152 m at the start of observations from the plane, but lifted to 396 m by the time observations ended; thus observations from the plane were carried out from 152-396 m. Only blow intervals could be recorded from both shore and the aircraft. The whales that were observed were approximately 2.5-3.2 km from the observation post on Herschel Island. We are not certain that the aircraft data are from exactly the same whales, but they were within the same area.

The lengths of the blow intervals recorded from Herschel Island were statistically similar before the aircraft arrived and while it was present (Table 7; $t = 0.10$, $df = 22$, $p>0.6$). Blow intervals observed from Herschel were also statistically similar to those observed from the aircraft ($t = 0.51$, $df = 51$, $p>0.5$). Thus, with respect to blow interval, there was no detectable effect of the aircraft on 3 September 1981.

In summary, whales almost always dove when the observation aircraft circled them at an altitude of 305 m or less, and they sometimes dove (in 1981) when the aircraft was at 457 m. Blow intervals recorded from Herschel Island before and during the presence of our aircraft were similar. When we looked at all of the respiration and surfacing data collected in 1980-81 from two altitude ranges (457 to 580 m and 610 to 854 m), we found no major differences related to altitude of the aircraft. However, surface times tended to be slightly longer when observed from higher altitude.

On two occasions when we circled a group of whales at 610 m and then at lower altitudes there was a statistically significant reduction in blow interval and a suggestion that length of surfacing and blows/surfacing also decreased when the plane was at a lower altitude. In general, the data

Table 7. Blow intervals of whales observed near Herschel Island from land and from the Britten-Norman Islander, 3 September 1981.

Observation Platform	Period of Observation	Mean	s.d.	n
Herschel Island	Before aircraft arrived	10.75 s	4.62 s	8
	While aircraft present	10.94	4.22	16
	Combined	10.88	4.26	24
Aircraft	While aircraft present	11.72	6.99	29

strongly suggest that our aircraft usually affected the whales' behavior when it circled whales at 305 m or below, but usually did not have a major effect when it circled at 457 m. The usual reactions to the aircraft were some combination of reduced surface time, reduced blow intervals, and hasty initiation of a dive. We never detected any effect when the aircraft was at 610 m or above.

Reduced surface times and blows/surfacing were also noted during boat disturbance (see above) and airgun disturbance (see below). The reduced blow intervals during periods of probable aircraft disturbance are, however, not consistent with blow intervals during close approaches by the boat 'Sequel' (increased blow intervals) or during airgun experiments (no change in blow intervals). We have no explanation for the lack of consistency in blow intervals during the various types of probable disturbance.

Reactions of Bowheads to Seismic Exploration Noise

On two occasions we observed bowhead whales that were well within the area ensonified by an active seismic ship, the 'Arctic Surveyor'. In addition, in 1981 we conducted two controlled tests of reactions to an airgun. Airguns are one of the types of devices used to create sound impulses for seismic exploration.

Behavior of Bowheads near Seismic Vessel, 21 August 1980

Late in the evening of 21 August 1980, a seismic exploration vessel was operating in the general area where whales had been observed during recent days. It was not possible to reach the area until 22:25, when the light was failing and the potential for making detailed observations was limited. The sky was clear and there was a light breeze (<9 km/h) from the NE. A sonobuoy was deployed to monitor the sounds near the whales.

The boat, the 'Arctic Surveyor', was operating near 69°53'N, 132°47'W, in about 12 m of water. The devices being used were 'sleeve exploders'. Twelve rubber cylinders, each about 1.2 m long and 0.3 m in diameter, receive a charge of propane and oxygen and are ignited simultaneously to generate the required energy pulse. In 6 series of 'shots', there were 8 shots/series, and the interval between shots averaged 8 s (range: 6-10). Each series was separated from the next by a 'silent' period of about 50 s as the vessel moved to a new location.

The closest whales that we could discover were a group of at least seven located about 13 km 60°T from the vessel, in 12-13 m of water. The whales were active, apparently socializing. There was no apparent tendency for the whales to make any net movement away from or toward the seismic vessel. Because of the poor light conditions, it was difficult to follow individual whales at the surface, but some behavioral data were gathered (Fig. 9).

The whales were interacting quite vigorously. There appeared to be short chases. Two individuals sometimes surfaced simultaneously or nearly so, and on one occasion a whale surfaced in between two other whales that were close together. The duration of surfacings, the number of blows/surfacing, and the intervals between blows were all similar to or, at most, only slightly reduced from, those exhibited by apparently undisturbed whales observed in the same general area on the preceding and following days (Fig. 9). All three parameters were also similar to those for all presumably undisturbed bowheads observed in water ≤ 15 m deep (cf. Table 4 in 'Normal Behavior' section, Würsig et al. 1982; t-tests give $p>0.1$ for each parameter).

The underwater sounds produced by the seismic exploration vessel were frequent and very intense near the whales. Most energy was in the 100-200 Hz band. We were unable to make accurate measurements of these sounds, but our rough measurements on this date (135-146 dB//1 µPa) were consistent with the expected value 13 km from the ship (141 dB). The latter value is based on an equation developed from accurate measurements at several ranges (Greene 1982).

Behavior of Bowheads near Seismic Vessel, 25 August 1981

On 25 August 1981, we again observed bowheads relatively close to the active seismic vessel 'Arctic Surveyor'. The closest whales were 6-8 km from the boat, in water of depth 11 m, and there were other whales nearby out to about 20 km from the seismic boat. We had planned to conduct a controlled experimental disturbance using the airgun mounted on the 'Sequel', but the 'Arctic Surveyor' had so ensonified the area that was accessible to us that we could not do a valid experiment. Instead, we recorded the behavior of the whales about 6-8 km from the 'Arctic Surveyor', and then observed the response of whales to the 'Sequel' as it passed nearby (see 'Reactions of Bowheads to Boats', above). The level of the seismic sounds 8 km from the 'Arctic Surveyor' is about 150 dB//1 µPa (Greene 1982).

At least seven small groups of whales (1-3 animals per group) were visible in the area west of the 'Arctic Surveyor'; no whales were to the east. Most of these whales were oriented or moving slowly toward the south or southwest or were just milling. A Rayleigh test on the orientations indicated no significant directionality (mean vector length = 0.206, n = 26). Mud issued from the mouths of at least two whales, indicating feeding near the bottom. There was also considerable social activity. Numerous calls from bowheads, along with the seismic sounds, were recorded via a sonobuoy (Würsig et al. 1982: Table 5). The water was comparatively rough--sea state 3.

There was little evidence that surfacing and respiration characteristics were affected by the seismic noise on 25 August 1981, although the absence of 'undisturbed' control data from this date prevents specific comparisons. Figure 10 summarizes the data for the period of seismic noise preceding the

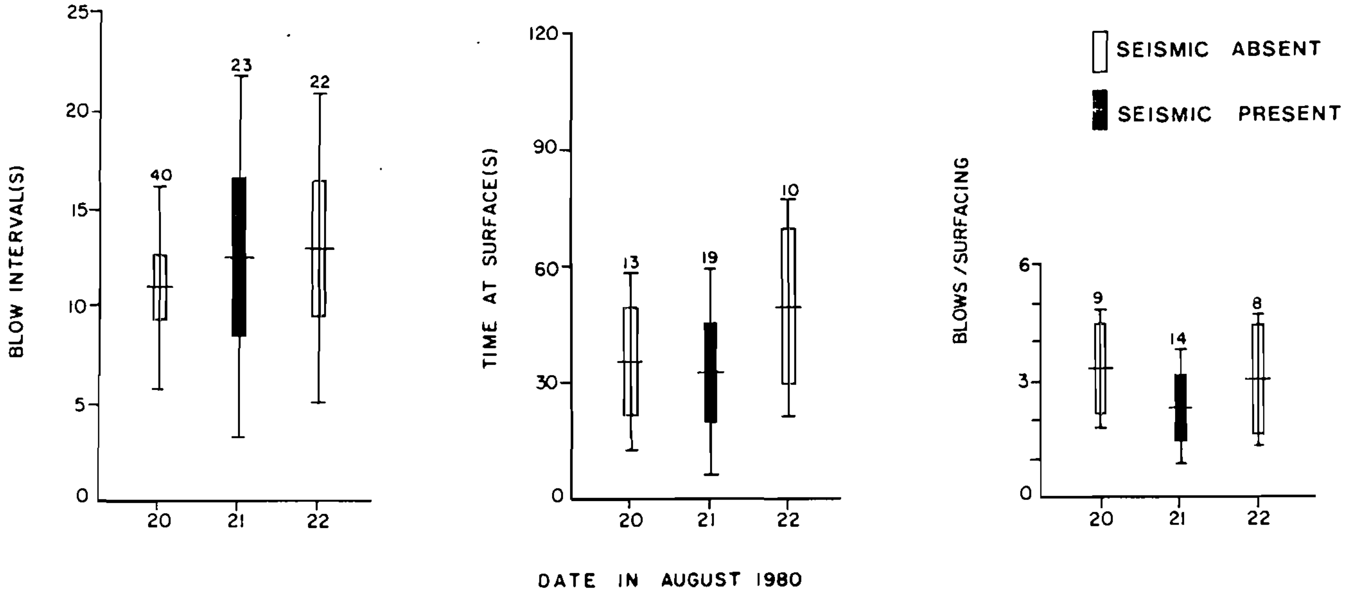


FIGURE 9. Surfacing, respiration characteristics of bowheads observed 13 km from the seismic vessel 'Arctic Surveyor' on 21 August 1980, and in the absence of disturbance on 20 and 22 August 1980. Presentation as in Fig. 6.

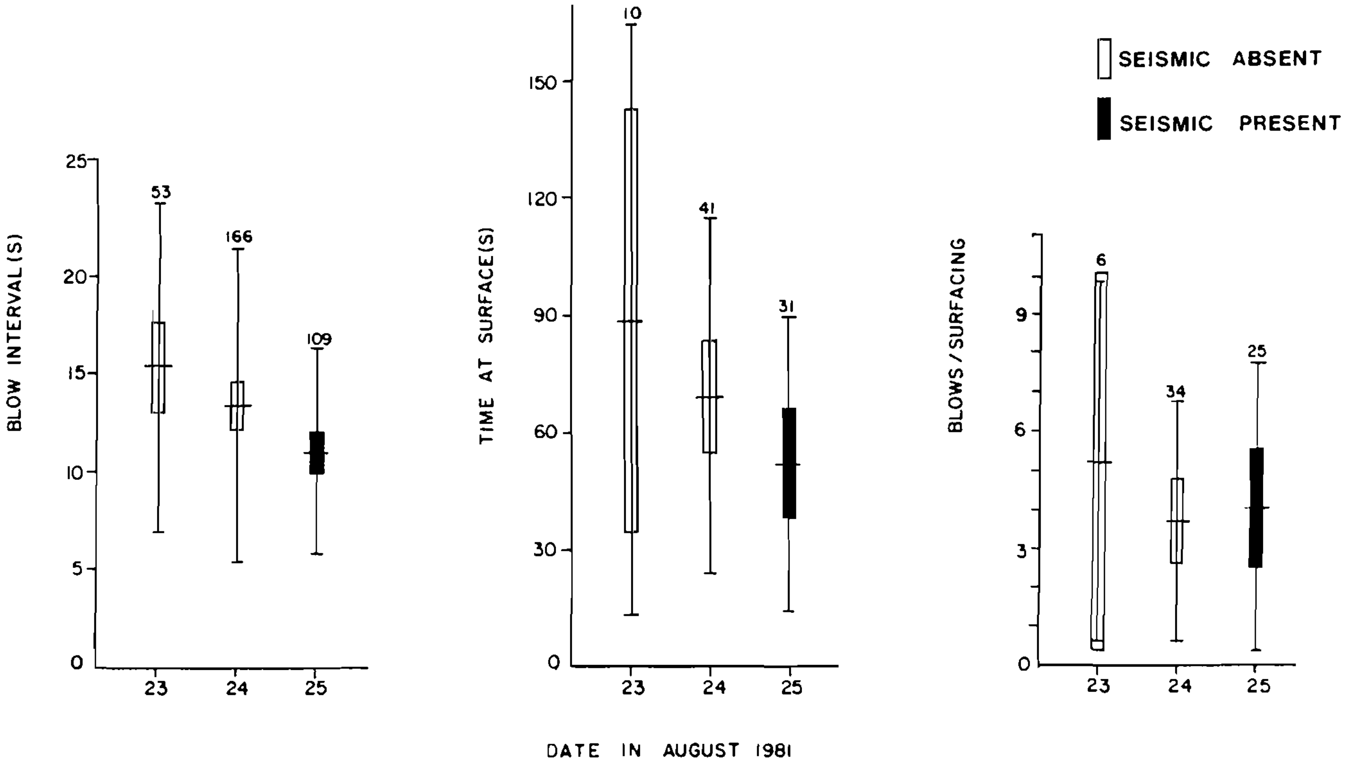


FIGURE 10. Surfacing and respiration characteristics of bowheads observed 8 km from the seismic vessel 'Arctic Surveyor' on 25 August 1981, and in the absence of disturbance on 23 and 24 August 1981. For 25 August, only the data collected before there was boat disturbance are considered. Presentation as in Fig. 6.

approach of the 'Sequel'. The number of blows per surfacing was similar to that of bowheads in the same general area northwest of Pullen Island, but somewhat farther offshore, on the two preceding days. However, the mean blow interval and mean surface time per surfacing were noticeably less than on previous days (Fig. 10). Statistical comparisons of results from 23-24 August vs. 25 August are not justified because water depths differed (11 m on 25 August vs. 23-29 m on 23-24 August). Water depth affects the expected values under undisturbed conditions (see Table 4 in Würsig et al. 1982). However, results from the period of seismic noise on 25 August can be compared with data from all presumably undisturbed bowheads in water $\leq$15 m deep. These comparisons showed no significant differences in surface times, blows/surfacing or blow intervals (t-tests, $p>0.05$ in each case).

Dive times recorded during the period of seismic noise preceding the approach of 'Sequel' averaged longer than those for presumably undisturbed whales in $\leq$15 m of water (5.3 ± 4.9 min vs. 1.0 ± 1.4 min). The biological significance of the difference in dive times is uncertain. In other situations in which dive times appeared to be affected by disturbance, dive times decreased rather than increased.

Airgun Experiments, 18-19 August 1981

On 18 and 19 August 1981, through the coordinated use of the aircraft and M.V. 'Sequel', we were able to conduct controlled observations of the behavior of bowhead whales in the presence of sounds produced by a 40 in^3 (655 cm^3) airgun deployed at a depth of 6 m behind the boat and fired every 10 s for 19-20 min. Table 8 shows the durations of the pre-airgun, airgun, and post-airgun phases. On 18 August, the boat circled slowly (5.6 km/h) around the whales at a radius of 5 km from the whales throughout all three phases of the experiment. Because of the lack of major response by the whales on 18 August, we repeated the experiment on 19 August at a distance of about 3 km. Airgun sound levels near the whales at the start of the airgun phases of these two experiments were at least 123 and 118 dB//1 μPa based on measurements obtained via sonobuoys. (The actual received level is unknown because of signal distortion at either the sonobuoy or the receiver stage.) Most energy was in the band 100-400 Hz.

Table 8. Durations of various phases of the airgun experiments, 18 and 19 August 1981.

Date	Phase	Boat-to-Whales Distance	Duration
18 Aug*	pre-airgun	5 km	83 min
	airgun	"	20 min
	post-airgun	"	69 min
19 Aug**	pre-airgun	2.5-3.5 km	96 min
	airgun	"	19 min
	post-airgun	"	40 min

* Observation aircraft circled at 457 m throughout experiment. Airgun was discharged from 19:49 to 20:09 MDT. Location of whales was 70°03'N, 134°46'W; water depth 23-28 m.

** Observation aircraft circled at 610 m throughout experiment. Airgun was discharged from 14:26 to 14:45 MDT. Location of whales was 70°03'N, 134°48'W; water depth 25 m.

Surface times and number of blows per surfacing were clearly affected during the airgun phase of the 5 km experiment, and there was evidence of similar trends during the 3 km experiment (Fig. 11; see Appendix 5 for details). When the airgun was discharged, the number of blows per surfacing was depressed--markedly on 18 August and slightly on 19 August. On 18 August the differences among pre-airgun, airgun and post-airgun values were statistically significant (Kruskal-Wallis H = 8.29, df = 2, $0.01<p<0.025$), and the values for the airgun period were significantly less than those during the control pre-airgun period (means 0.83 vs. 3.23; $p<0.05$ by Dunn's multiple comparison procedure, Hollander and Wolfe 1973). Unexpectedly, the effect was less pronounced and non-significant on 19 August, despite the fact that the airgun was closer to the whales (Mann-Whitney U for pre-airgun vs. airgun periods = 115.5, n = 29,9, $p>0.1$). Not surprisingly, the length of time spent at the surface followed the same pattern as the number of blows/surfacing (Fig. 11), with a significant effect on 18 August (H = 8.54, df = 2, $p<0.025$) but not on 19 August (H = 1.75, df = 2, $p>0.25$). As usual, blow intervals were more stable than blows/surfacing or surface times; blow intervals did not differ significantly among phases of either experiment (on 18 August, F = 0.12, df = 2,110, $p>>0.1$; on 19 August, F = 0.06, df = 2,166, $p>>0.1$).

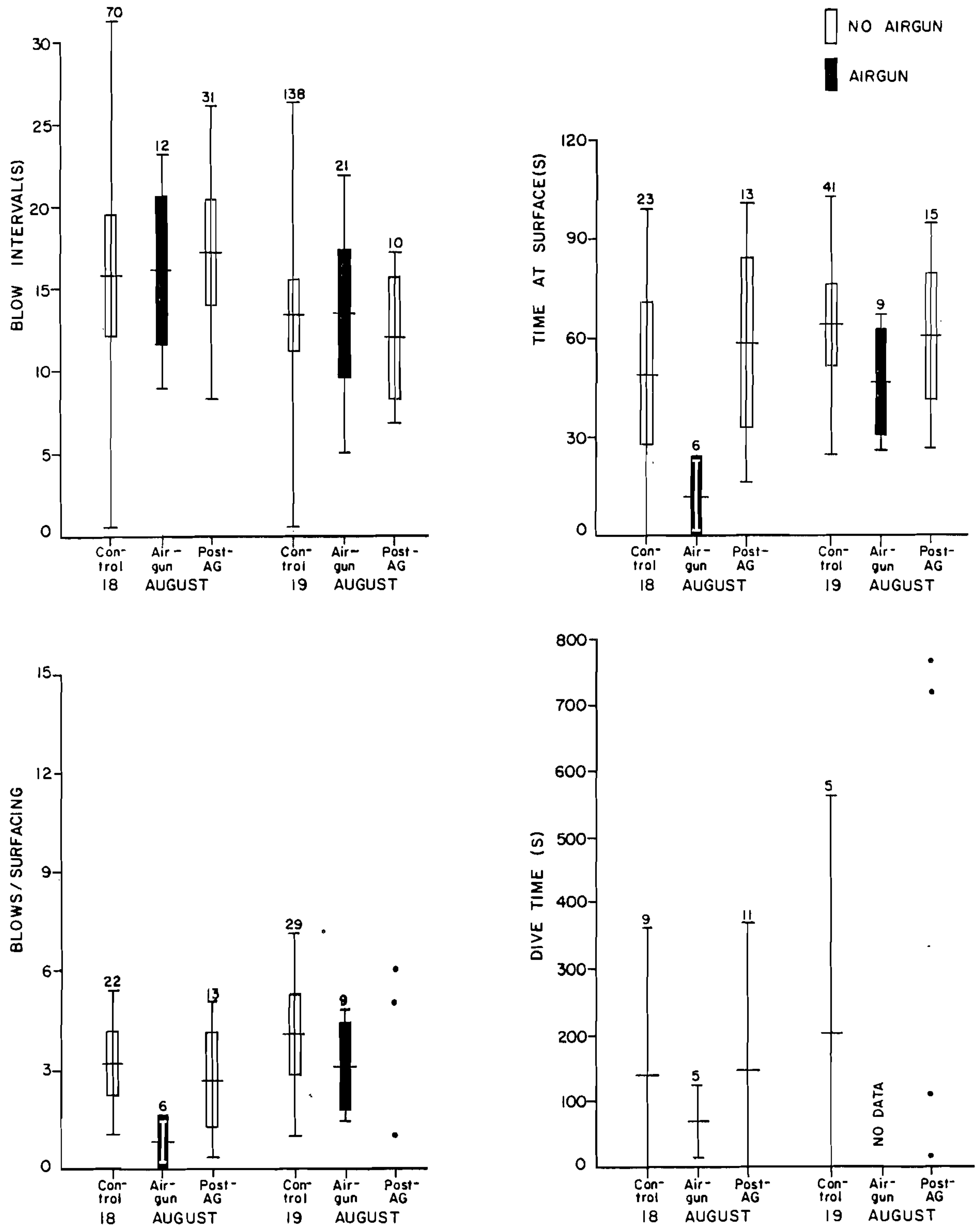


FIGURE 11. Surfacing, respiration and dive characteristics of bowheads observed before, during and after airgun experiments on 18 and 19 August 1981. Airgun-whale distance was about 5 km on 18 August and 2.5-3.5 km on 19 August. Presentation as in Fig. 6.

Only limited data could be gathered on the dive times of individual whales, owing to the difficulty of following the behavior of identifiable individuals. The few dive times recorded were quite variable (Fig. 11), and no conclusions about reactions to the airgun are possible. The five dives recorded during the airgun phase on 18 August were all short (4-134 s), but not significantly less than those during the pre- and post-airgun periods ($H = 0.01$, $df = 2$, $p>0.5$).

The whales observed on 18 August were echelon feeding at and just below the surface. (During echelon feeding, groups of 2-14 bowheads feed in a specific formation; each animal is behind the preceding one and offset to the side by 1/2 to 3 body widths--Würsig et al. 1982). We recorded the number of animals within each echelon at several minute intervals (Table 9). A total of about 19 individuals were under observation. During the pre-airgun, airgun and post-airgun phases, the mean numbers of whales comprising the echelons were 4.67, 2.83 and 3.67, respectively. The differences cannot be tested statistically because of partial lack of independence, but there did appear to be an effect of the airgun on the number of animals comprising the echelons. Nonetheless, the echelons continued to exist and the whales were still feeding during the airgun and post-airgun phases. Appendix 6 describes the behavior and path of one recognizable bowhead that was observed for almost 3 h during all phases of the experiment.

Table 9. The numbers of whales comprising echelons during the airgun experiment on 18 August 1981.

Phase	Mean	s.d.	n
pre-airgun	4.67	2.198	21
airgun	2.83	1.329	6
post-airgun	3.67	1.557	12

There was a dramatic decrease in sound production by the whales during the 5 km airgun test. During 20 min of airgun activity, no bowhead sounds were heard via the sonobuoy. In contrast, 11 calls and 43 blows were heard in 88 min of recording during the pre-airgun control period, and 57 calls and

83 blows were heard in 126 min of post-airgun recording. Airgun noise masked the recording for only 1 or 2 s out of every 10 s during the airgun phase, so the difference is not an artefact of any significant reduction in our ability to detect bowhead sounds during the airgun phase. In contrast, one bowhead call was detected during the airgun phase of the 3 km experiment, and numerous bowhead calls were recorded during some days when sounds from full-scale seismic operations were recorded through the sonobuoys (Würsig et al. 1982: Table 5).

We looked at orientations of whales on 19 August in two ways: with respect to (1) true north, and (2) the location of the 'Sequel' and the airgun.

1. The animals were oriented significantly and in the same direction (southwest) during each phase of the experiment. However, the variability of directions around the southwesterly mean was less during the airgun and post-airgun phases than during the control pre-airgun phase (Table 10). Similarly, another group of investigators (Davis et al. 1982) saw numerous bowheads about 25 km farther west on the morning of 19 August; they too were oriented southwest (LGL Ltd., unpubl. data). Thus, the overall southwest orientation of the whales was not noticeably affected by the airgun.

2. Orientations relative to 'Sequel' differed among phases of the experiment, but this may have been a result of the overall SW orientation rather than to any reaction to the airgun. During the pre-airgun phase, 'Sequel' completed about 70% of a circle around the whales, and orientations toward and away from 'Sequel' were equally divided (32:32). During the airgun phase, 'Sequel' was NNW-NNE of the whales, and there were six orientations toward and 11 away. The difference from a 1:1 ratio was not significant (chi-square = 1.47, df = 1), but the tendency for orientation away would be expected for animals travelling SW. Similarly, during the post-airgun phase, 'Sequel' was NNE-SSE of the whales, and there were 22 orientations away and only six toward (chi-square = 9.14, df = 1, $p<0.005$). The tendency for orientation away again would be expected for animals travelling SW.

Thus there was no clear evidence that noise from the airgun 3 km away affected the orientations of bowheads. The only hint of an effect is that there was less variability around the prevailing southwestward mean orientation during the airgun and post-airgun phases than during the pre-airgun phase. A southwestward orientation was generally away from the airgun and boat during the airgun and post-airgun phases.

Table 10. Absolute orientations of whales during the airgun experiment on 19 August 1981.

Phase	Vector mean (°)	Length of Mean Vector*	n
Pre-airgun	210°T	0.378	37
Airgun	220°	0.603	9
Post-airgun	233°	0.719	13
All	219°	0.480	59

* This is a measure of variability. If there were no variation, the length of the mean vector would be 1.0; if orientations were uniformly distributed in all directions, the value would be 0.0.

Industry Sightings

Bowheads were reportedly seen from the seismic ship 'GSI Mariner' on at least seven days in the 30 July-26 August 1981 period. This ship was using an array of airguns, and most sightings were far offshore north of Cape Dalhousie, N.W.T. (Fig. 1). Capt. D. Weston of the 'GSI Mariner' reported sighting a total of at least 20 bowheads in 9 groups of sizes 1-4. Their estimated distances of closest approach to the ship were 1-4 n.mi. (2-7 km). We do not have specific information about the activity of the ship at the time of each sighting, but the airguns were presumably being fired at the times of most or all sightings.

In summary, our observations indicate that bowheads in the presence of sounds from underwater seismic exploration show a considerable degree of tolerance. In both 1980 and 1981 we observed whales in shallow water about 6-13 km from full-scale seismic operations using the sleeve-exploder technique. The seismic sound levels 8 and 13 km from that particular seismic ship were about 150 and 141 dB//1 μPa (Greene 1982). With only two observations, a cautious interpretation is necessary, but the whales tolerated this noise level to some extent. There was no conclusive evidence of alterations in surfacing and respiration characteristics relative to those in similar water depths in the absence of seismic noise. When the seismic vessel was

6-8 km away, dive times were significantly longer than is typical in shallow water; however, we have no evidence that the longer dives were indicative of disturbance--the opposite is more commonly true. Bowhead sounds were recorded in the presence of seismic noise, including during the observations 6-8 km from the seismic ship.

Two small-scale controlled experiments using a 40 in^3 airgun operated from a small boat again indicated some tolerance, including continued echelon feeding during the airgun trial at 5 km on 18 August. Airgun sound levels near the whales during these experiments were at least 123 and 118 dB, and the source level of the airgun is about 222 dB at 1 m. Surface times and blows/per surfacing did decrease significantly during one of the airgun trials, and bowheads ceased calling during that trial. Further information is needed concerning the nature of the whales' responses to seismic sounds.

Tolerance by Bowheads of Marine Industrial Operations

It was not possible, in either 1980 or 1981, to conduct controlled experimental tests of reactions of bowheads to underwater playback of recorded industrial noise. However, bowheads were observed in a number of situations that indicated some degree of tolerance of ongoing industrial operations--near an artificial island under construction and near an operating drillship. In both of these circumstances, we also obtained information about noise characteristics in the water.

Artificial Island Construction

During our initial flights in 1980 to observe the normal (undisturbed) behavior of bowheads, we found that there were many bowheads near Issungnak, an artificial island located in about 19 m of water off the Mackenzie Delta (Fig. 1). During August 1980, Esso Resources Canada Ltd. was building up and improving Issungnak. This operation included a large suction dredge ('Beaver Mackenzie', described in 'Methods'), a barge camp ('Arctic Breaker'), 2-4 tug boats, and 1-2 crew boats. Construction of Issungnak began in 1978 and continued through the summer of 1979. The island was used as a platform for exploration drilling during the winter of 1979-80. Encouraging results from that drilling made it desirable to improve the island during summer 1980 and to drill an additional well in the winter of 1980-81. Thus, there had been a similar level of activity in this area for three years.

Many bowheads were found during systematic surveys of the Issungnak area during August 1980 (Table 11). None were seen during the 24 July survey, which apparently preceded their arrival in this area. In general, most were in the northern part of the survey area in water 18 m or more in depth (Fig. 12, 13). The densities of bowheads observed 'on-transect' during the five surveys in the period 5-12 August ranged from 0.028 to 0.055 whales/km2 (Table 11). The somewhat lower densities of whales seen during surveys for Esso on 5 and 9 August (0.028-0.031 whales/km2) compared to those seen during surveys for BLM on 9, 11 and 12 August (0.042-0.055 whales/km2) were probably a consequence of the different areas surveyed during the two projects. A

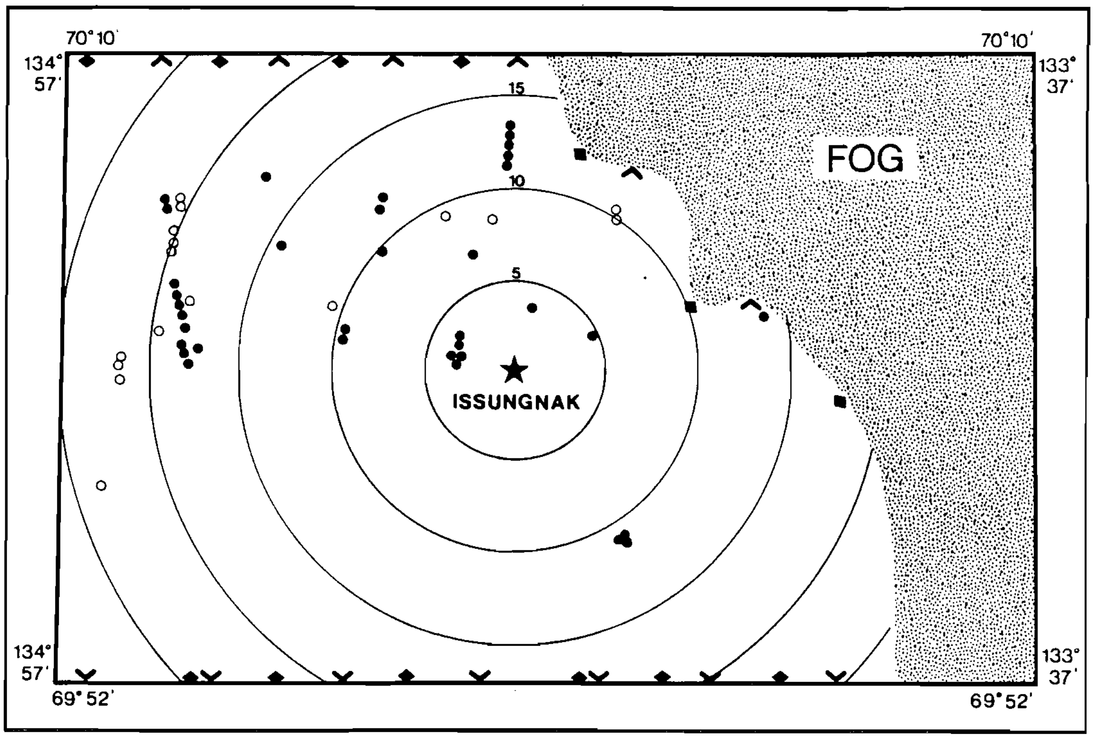
Table 11. Observations of bowhead whales during surveys of the Issungnak area, August 1980.

Date	Number Seen (on-transect)	Length of Survey (km)*	Area Surveyed (km^2)	Observed Densities (whales/km^2)	Distance of Closest Bowhead from Island (km)**	No. Seen Within 5 km of the Island***	No. Seen 5-10 km from the Island***
BLM Surveys							
9 Aug	35	394	635	0.055	3.2	7	7
11 Aug	27	306	492	0.055	10.4	0	0
12 Aug	37	554	892	0.042	5.5	0	7
22 Aug	23	554	892	0.026	12.0	0	0
Esso Surveys							
5 Aug	19	425	684	0.028	4.8	1	4
9 Aug	21	425	684	0.031	0.8	12	11

* In the case of the BLM surveys, the actual length (rather than the theoretical straight-line length) is given.

** The approximate distance of the closest bowhead detected by the aerial surveyors is given; other bowheads that were below the surface or otherwise not detected by the observers may have been present.

*** Includes off-transect sightings.



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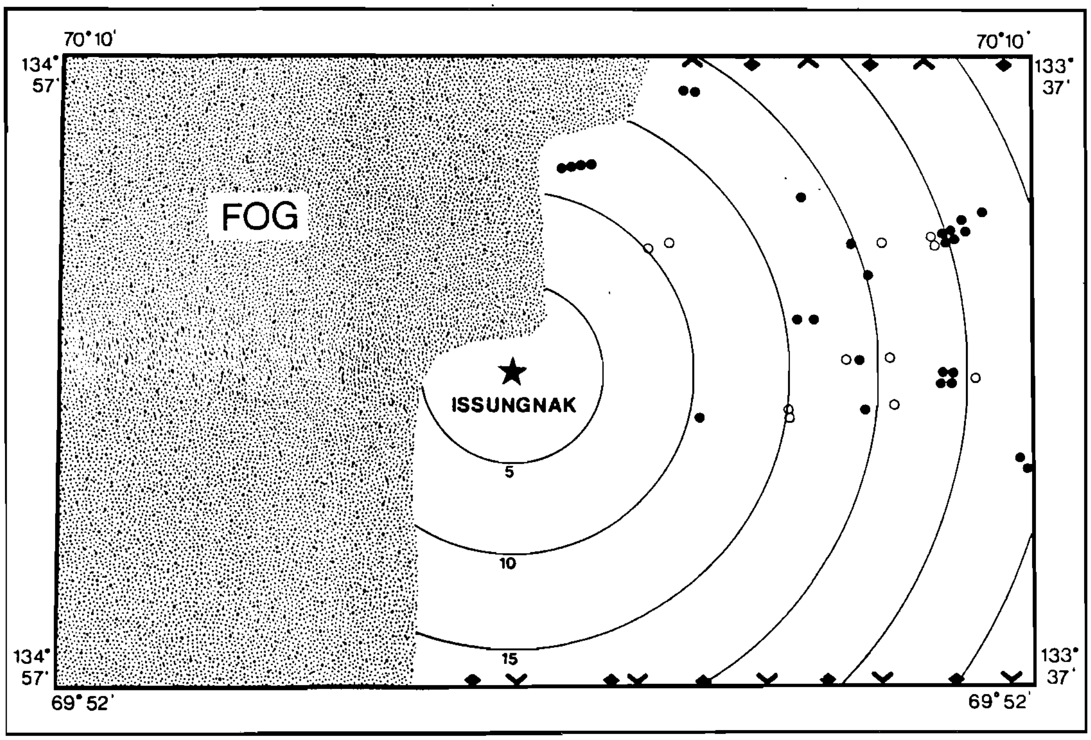

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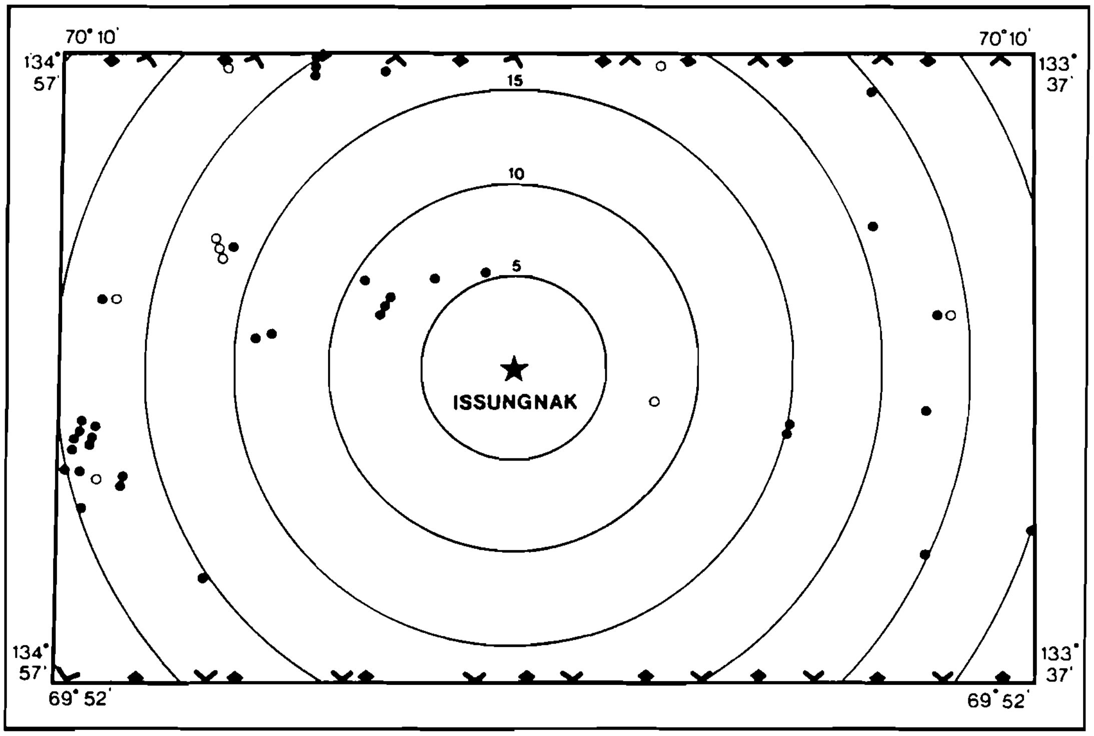
FIGURE 12. Observations of bowhead whales made during four systematic surveys of the Issungnak area. Solid dot = 1 whale within the 0.8 km transect strip; open dot = 1 whale sighted 'off-transect'; 'V' symbol = start of survey line; solid diamond = end of survey line. Concentric circles are at intervals of 5 km.



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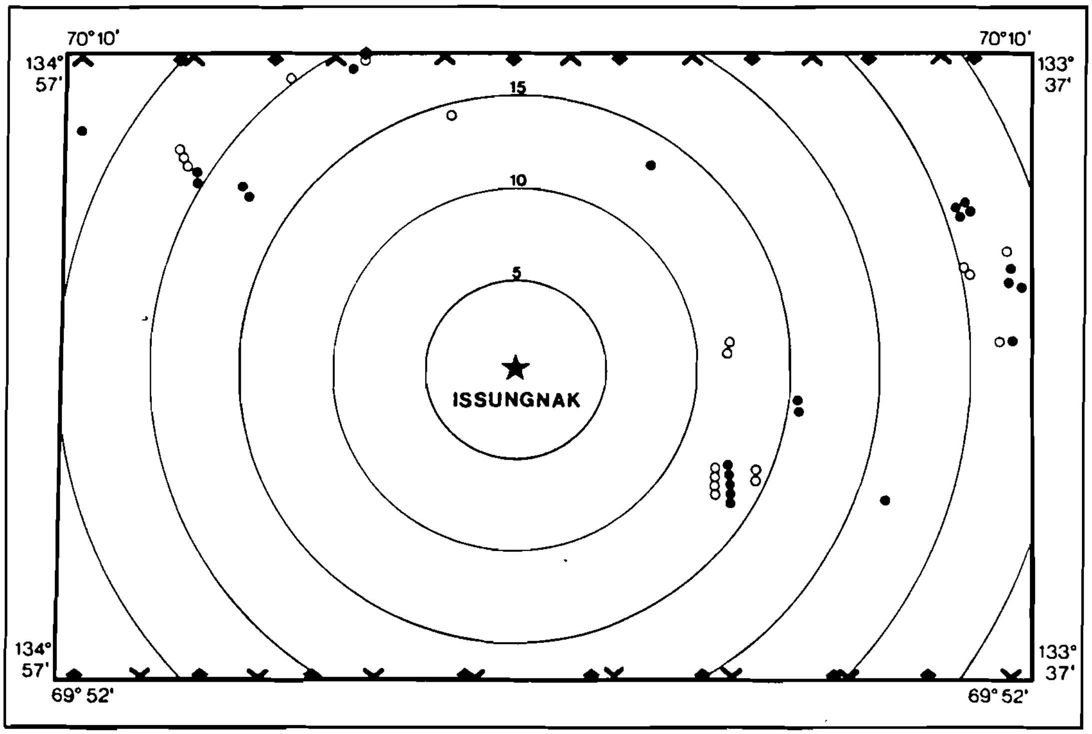

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FIGURE 12 (cont.).

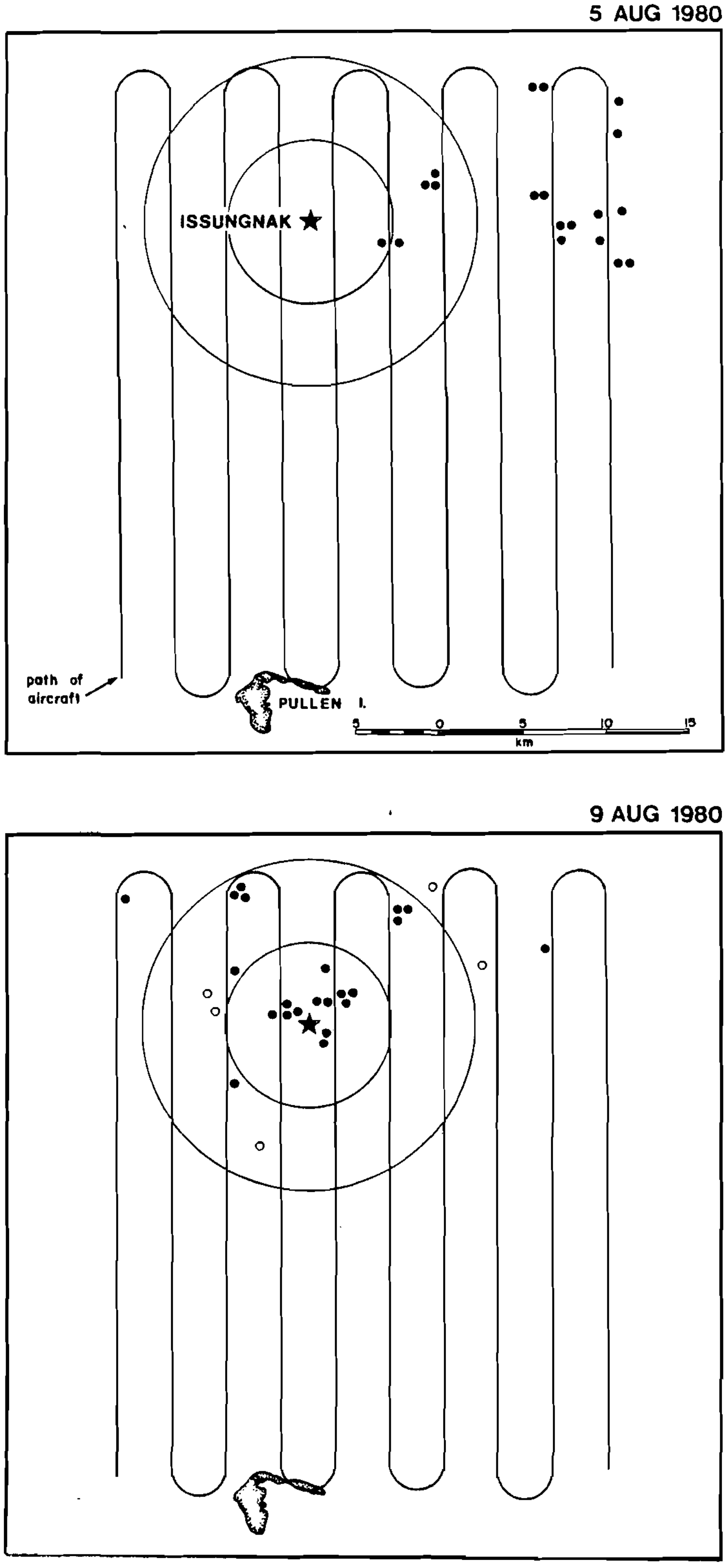

FIGURE 13. Observations of bowhead whales made during two systematic surveys of the Issungnak-Pullen Island area. Closed dots indicated individuals within the 0.8 km transect strip; open dots indicate individuals observed outside the transect strip. No bowheads were seen during the similar survey flown on 24 July. Circles denote radii of 5 and 10 km.

higher proportion of the area surveyed for Esso was shallow, and few bowheads were seen there.

The lower density (0.026 whales/km^2) recorded during the survey on 22 August probably reflects an actual decrease in the number of whales present in the Issungnak region; at that time large numbers of whales were present to the east off the Tuktoyaktuk Peninsula, where they had not been present earlier in August (Fraker and Fraker 1981:69; Renaud and Davis 1981; Würsig et al. 1982). The influx into the area off the Tuktoyaktuk Peninsula in late August involved at least several hundred whales (Renaud and Davis 1981)--far more than the number found near Issungnak earlier. Thus, it seems clear that the influx into the Tuktoyaktuk Peninsula area was part of a general movement of the population of whales, and cannot be attributed solely to an exodus from the Issungnak area.

Several whales seen during the aerial surveys were quite close to the island construction operation at the Issungnak site. The closest individuals seen during aerial surveys were within 800 m (Fig. 13). A total of 20 bowheads were sighted within 5 km of the island during the six surveys in August (Table 11; Fig. 12, 13). These records probably include some repeated sightings of the same animals, but 12 bowheads were seen within 5 km of Issungnak during one survey on 9 August. A total of 49 bowheads were seen within 10 km of Issungnak, including 23 during the 9 August survey for Esso.

Because of the obviously uneven and variable distribution of bowheads within the surveyed areas (Fig. 12, 13), it is not possible to determine whether there was significant avoidance of (or attraction to) the immediate area of construction. Data from 12 and especially 22 August could be interpreted to indicate some avoidance of Issungnak, whereas the BLM data from 9 August suggest little effect (Fig. 12). Additional data from 9 August suggest that the density of bowheads was higher within a few kilometres of Issungnak (Fig. 13). Despite this variability, the results show that bowheads commonly did occur near the construction site in August of 1980.

Also, a total of 18 sightings of one or more whales were reported by industry personnel working in the Issungnak area in 1980 (Table 12). The

Table 12. Observations by industry personnel of bowhead whales near Issungnak artificial island, 1980.

Date Time	Number of Whales	Location	Water Depth (m)	Estimated Closest Approach (km)	Orientations (true)	Remarks	Observer & Organization
2 Aug	40-50	69°59'N, 134°25'W	12	0.6	S	Whales appeared to be travelling; vessel was the 'Imperial Sarpik',	Ed Kehoe ERCL*
3-4 Aug	7-12	Issungnak area	18	0.1	-	Whales reportedly did not seem concerned by boat; spent time lying at surface and diving; vessel was 'J. Mattson'.	P. Harrison ATL**
4 Aug/10:00	8	70°01'N, 134°18'W	18	0.9	200°	Vessel was the barge camp 'Arctic Breaker'	B. Cox ERCL
4 Aug 19:30	20-30	5 km from Issungnak	-	-	NW	-	N. Sikkens
3 or 4 Aug	3	Issungnak area	18	0.016	-	Whales stayed about 12 h near the barge camp 'Arctic Breaker'; one approached to within 16 m	H. Grainger ERCL
5 Aug 02:00-04:00	12	5.6-9.3 km W of Issungnak	-	0.9	W to NW and E	Whales were diving and may have been feeding; no apparent reaction to 'Arctic Hooper' 0.9-3.7 km away	I. Rainsford ATL
6 Aug 02:00-04:00	18	9.3 km W of Issungnak	-	0.9	W	'Arctic Hooper' was 0.9-3.7 km away	I. Rainsford ATL
6 Aug/04:00	6	70°01'N, 134°20'W	20	0.4	W	Whales appeared to be circling the dredge 'Beaver Mackenzie' 0.4 km away	A.M. Peters
7 Aug/02:00	4	70°01'N, 134°20'W	20	0.5	090°	Whales approached to within 0.5 km of the dredge	L. Anderson

Continued...

Table 12. Continued.

Date Time	Number of Whales	Location	Water Depth (m)	Estimated Closest Approach (km)	Orientations (true)	Remarks	Observer & Organization
7 Aug/17:00	2	70°01'N, 134°20'W	20	1.6	090°	Whales were 1.6 km from the dredge 'Beaver Mackenzie'	B. Gojevic
7 Aug/19:00	3	70°01'N, 134°20'W	20	1.8-5.6	090°	Whales came within 3.7-5.6 km of the dredge 'Beaver Mackenzie'	L. Anderson
7 Aug/22:00	1	70°01'N, 134°20'W	20	1.8-5.6	090°	Whale passed by the dredge 'Beaver Mackenzie' 1.8-5.6 km away	A. Thorpe
9 Aug/03:00	1	70°01'N, 134°20'W	20	1.8-5.6	090°	Whales passed by the dredge 'Beaver Mackenzie' 1.8-5.6 km away	A. Thorpe
9 Aug 01:00-03:00	3	70°01'N, 134°20'W	20	0.5	270°	Whale milled and dove in the area, probably feeding. Then headed west, past the dredge 'Beaver Mackenzie' 2.8 km away	I. Rainsford, ATL
9 Aug/02:15	1	70°01'N, 134°20'W	20	3.7-5.6	090°	Whale passed by the dredge 'Beaver Mackenzie' 3.7-5.6 km away	A. Thorpe
10 Aug/13:00	2	70°01'N, 134°20'W	20	3.7-5.6	090°	Whales passed by the dredge 'Beaver Mackenzie' 3.7-5.6 km away	L. Anderson
18 Aug	4	70°01'N, 134°20'W	19	0.5	180°	Vessel was 'Arctic Pelly', wind was NNE at 20+ knots; 4-6' swells; air temp. 4°C; snow squalls	A. Fergusson/ R. Roy, ATL
11 Sept/14:00	1	Issungnak area	20	0.6	W	Whale approached barge camp 'Arctic Breaker' to within 0.6 km	H. Grainger ERCL

* ERCL = Esso Resources Canada Limited.

** ATL = Arctic Transportation Limited.

sightings were made from the dredge 'Beaver Mackenzie', the barge camp 'Arctic Breaker', and vessels operating in the immediate vicinity. Most of these sightings were made in the first half of August. Several sightings were reported to be within 0.5 km of the vessel from which the observation was made. One group of 3 whales apparently stayed near the 'Arctic Breaker' for about 12 h, with one whale reportedly coming within about 16 m of the barge camp.

Sightings by industry personnel and during our systematic surveys suggest that bowheads were not greatly disturbed by construction activities in the Issungnak area. We do not know what the industrial sound environment was during the specific periods when these observations were made. However, dredging was in progress throughout most of August 1980. The strongest tone produced by the dredge (at 380 Hz) has a level of about 109 dB//1 µPa at a range of 1 km, and 97 dB at 5 km (Greene 1982). Thus, at least some whales appear to tolerate both (1) the physical presence of the artificial islands, boats, dredge, etc., and (2) the sounds that are produced.

In 1981, bowheads did not occur in large numbers anywhere in the Mackenzie estuary region, and no fine-scale systematic surveys were done around the sites where islands were being built in that year.

Presence of Bowheads Near Drillships

On 23 August 1981 from 18:15 to 19:17 we observed a group of at least eight bowheads about 15-20 km west of 'Explorer II', which was at the North Issungnak site (70°06'N, 134°27'W). These whales were feeding and actively socializing. Echelon feeding was noted. We heard may vocalizations over the sonobuoy, and we could hear sounds of the drillship which was drilling at the time.

At 19:17 we noted another group of whales about 4 km from the drillship. After dropping a sonobuoy at this location (water depth 28 m), we observed these whales from 19:34 until 20:20. This group included two recognizable adults plus a yearling. The adults were involved in social interactions, and strong noise from the drillship was detected by the sonobuoy.

Figure 14 shows the surfacing, respiration and dive time data from these observations (see Appendix 7 for details). It must be recognized that these are uncontrolled data derived from only a few whales. Different individual whales were observed in the two situations, and drillship noise was detected by sonobuoys at both locations. Blow intervals were similar for the two groups of whales (Fig. 14; $t = 0.46$, $df = 125$, $p>0.5$). However, surface time per surfacing, number of blows per surfacing and dive times were all much longer at 4 km than at 15 km from the drillship; the difference was significant in each case:

Surface times	$t' = 2.35$	$df = 25.7$	$0.02<p<0.05$
Blows/surfacing	$t' = 2.96$	$df = 21.0$	$0.001<p<0.01$
Dive times	$U = 0$	$n = 11, 5$	$p<0.002$

Here, t' is the Student's t statistic assuming unequal variance (Johnson and Leone 1964), and U is the Mann-Whitney U statistic. We also compared the results obtained from whales 4 km from the drillship with those from all 'presumably undisturbed' whales seen in water 16-30 m deep (cf. Table 4 in Würsig et al. 1982). Blows/surfacing and dive times were significantly greater 4 km from the drillship, whereas blow intervals and surface times did not differ significantly.

In the absence of pre- or post-drilling control data from the same individual whales, it is impossible to determine whether the above-noted differences were a result of the drillship's presence or some other factor. Unfortunately, this was the only occasion in either 1980 or 1981 when we were able to observe bowhead behavior within a few kilometres of a drillship and in the absence of other potential sources of disturbance. However, numerous whales including at least two calves were observed about 8 km west of 'Explorer II' on 24 August 1981; these whales were exposed to boat noise as well as drillship noise. Some echelon feeding was observed. We also found some bowheads 15-20 km west of 'Explorer II' during a grid survey on 13 August 1981, and numerous bowheads in that area from about 18 to 23 August 1981 (Würsig et al. 1982: Table 2). Bad weather prevented flights on 14-17 August; bowheads may have been present 15-20 km from the drillship throughout that period.

Industry personnel reported sightings of bowheads near the drillships 'Explorer IV' and 'Explorer III' on several occasions from mid-July to early

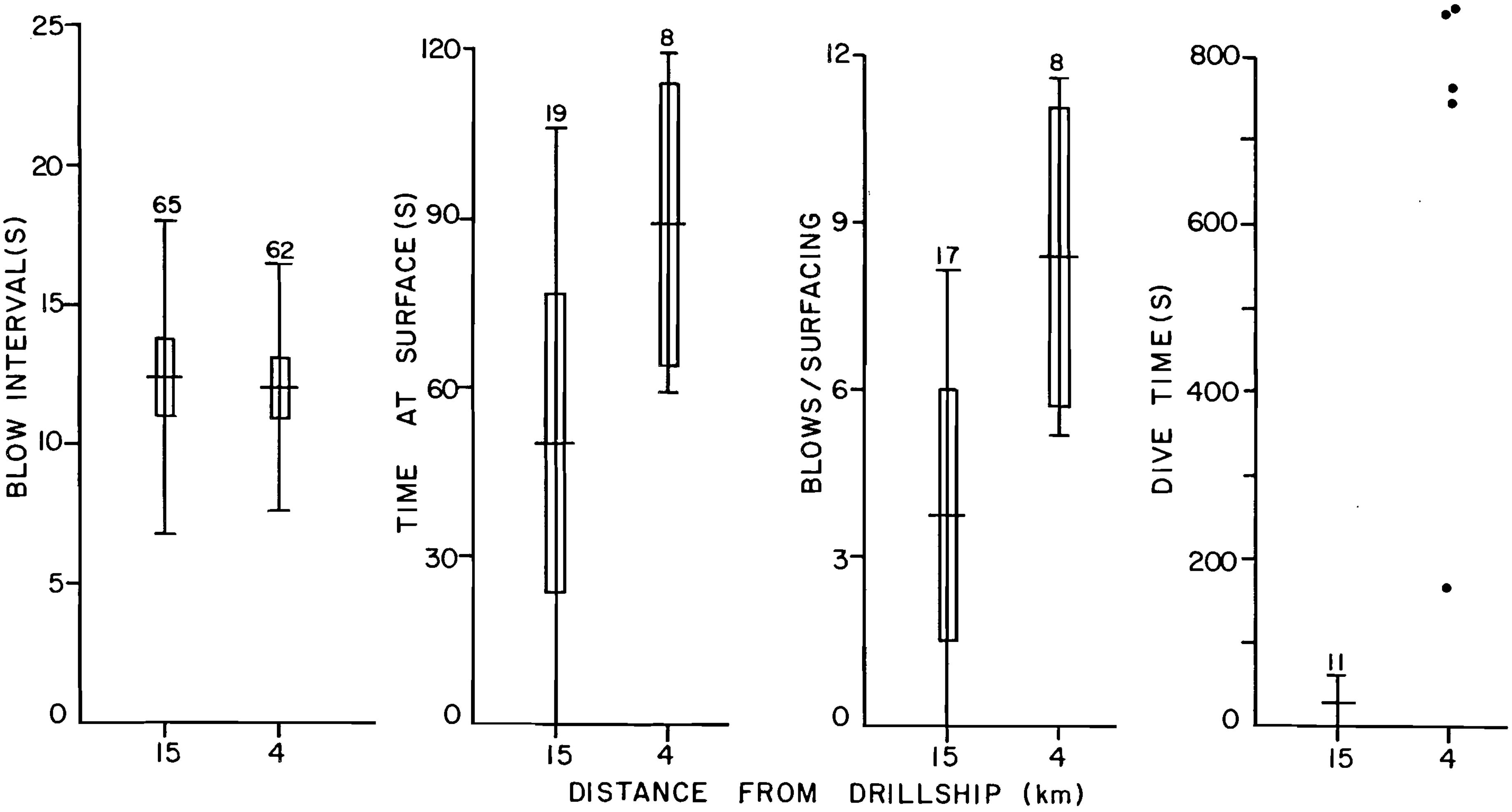

FIGURE 14. Surfacing, respiration and dive characteristics of bowheads observed 15 and 4 km from a drillship on 23 August 1981. Presentation as in Fig. 6.

August 1980. The distance of the whale(s) from the drillship was estimated for seven of these sightings as 0.2-5 km. Five of these seven sightings were at the Dome Orvilruk drilling site (70°23'N, 136°31'W).

The strongest tonal sound recorded from the 'Explorer II' during measurements at North Issungnak on 6 August 1981 was about 278 Hz. Its levels at distances of 1, 4 and 8 km from the drillship were about 121, 111 and 102 dB//1 μPa (Greene 1982).

In summary, bowheads sometimes approach within a few kilometres of drillships, where they engage in both feeding and socializing. It is not known whether numbers per unit area are less near drillships than elsewhere. Also, it is uncertain whether the drillship 'Explorer II' was responsible for the behavior differences that we noted on 23 August 1981 between whales at ranges of 15 and 4 km from the drillship.

DISCUSSION

Reactions of Bowheads to Boats

Boats and ships are the most widespread source of potential disturbance to which bowheads are exposed on their summering grounds in the eastern Beaufort Sea. Some western arctic bowheads also encounter marine traffic during their fall migration north of Alaska and possibly elsewhere en route to wintering grounds in the Bering Sea. Boats are a source of potential disturbance during exploration and development in lease areas off northern Alaska, and interactions may be especially probable when work extends to waters deeper than a few metres. Bowheads currently are rarely exposed to marine traffic on their wintering grounds or during spring migration, except for an occasional icebreaker. Shipping is a major source of potential disturbance because ships are mobile, relatively numerous, and often quite noisy.

Bowheads respond at least mildly to boats even when they are at a considerable distance. One of us (BW) has observed the reactions of both bowheads and gray whales to boats; bowheads are considerably more sensitive. When the engines of the 'Imperial Adgo' were idling but disengaged from the propellers, whales at a distance of 3-4 km responded even though the boat remained stationary. The mean surface time per surfacing became shorter and its variability increased (Fig. 4). The large number of observations made at closer range from the 'Adgo' itself indicated that the boat had no major effect while it remained silent, even when it was within 900 m. However, when its engines were idling, the whales tended to orient away (Fig. 3).

On 27 August 1980, while the 'Adgo' remained stationary 3-4 km away from the whales with its engines idling, the responses must have been to the boat's underwater sound. For frequencies below 500 Hz, the sound levels received by a sonobuoy near the whales were above low ambient levels by about 15-25 dB, and above higher ambient levels by about 0-5 dB (Greene 1982: Figs. 5 and 6 vs. 10). For frequencies 500-2000 Hz, the received level was about 5-20 dB above ambient levels. Most bowhead phonations are below 2000 Hz (Ljungblad et al. 1982; Würsig et al. 1982), and presumably the whales can hear well in this range.

It is possible that the response of the whales to the noise of the idling engines resulted from the novelty of the situation, i.e. the sudden onset of the noise after the boat had remained silent for some time. Bowheads showed considerable tolerance of ongoing noise from seismic surveys, dredges and boats, and thus it is possible that bowheads would habituate to the continuous sound of a boat's idling engines.

When boats were moving within 1-3 km of bowheads, the whales reacted by spending significantly briefer periods at the surface and by quickly moving away. The decreased lengths of surfacings were noted during the 'Adgo' experiment on 27 August 1980 ($p<0.001$), the 'Sequel' experiment on 25 August 1981 ($p<0.025$), and the 'Arctic Surveyor' observations on 23 August 1981. The number of respirations per surfacing was also reduced or unusually low during each of these occasions. Furthermore, dives tended to be briefer when a boat was nearby on the two such occasions when dive times could be recorded (the 'Sequel' and 'Arctic Surveyor' incidents).

Observations from the 'Adgo' showed that bowheads tended to orient away from the boat even when it was somewhat more than 900 m away (Fig. 3). For whales $\leq$900 m from the 'Adgo' the orientation away was more pronounced when the boat was travelling than when it's engines were idling.

Whales that were directly in the path of a boat initially attempted to outrun it. This orientation away from the boat took place as the vessel came within 0.8-1 km during the 'Adgo' and 'Supplier IV' encounters in 1980, but at 2-3 km during the 'Arctic Surveyor' and 'Sequel' encounters in 1981. This difference does not seem to be attributable to the size of boat and the associated strength of the boat noise; 'Adgo' and 'Sequel' are both small vessels, and 'Supplier IV' and 'Arctic Surveyor' are both much larger. One possible explanation is that the whales observed near boats in 1981 were affected not only by boats, but also by other industrial activities going on nearby before and during the close approach by a boat (seismic exploration near 'Sequel'; drillship near 'Arctic Surveyor').

As a boat approached to within a few hundred metres, the whales usually turned and swam perpendicular to the boat's path. However, the animals sometimes dove or turned directly in front of the boat at a distance of 100 m or less. On one occasion, the 'Supplier IV' encounter, the highly directed movement away from the boat's track ceased before the boat had travelled 1 km past the whales, and the whales were still in the area 3 h later. However, on two other occasions, the 'Arctic Surveyor' and 'Sequel' encounters, bowheads continued to move perpendicular to and away from the boat's track when the boat was about 1.5 km beyond the whales. Even then there was no indication that the whales moved out of the area. By the time that the 'Sequel' was 5.6 km past the whales, they had stopped travelling and were milling.

Although bowheads probably do not leave an area after a close approach by a boat, the disturbance effect may linger for a considerable period. Orientations of bowheads observed 15-45 min after the 'Supplier IV' passed were significantly different from those before the disturbance (Table 4). Also, when the 'Adgo' passed a group of whales, their inter-individual distances increased significantly ($p<0.001$). This effect persisted after the 'Adgo' was >4 km away (Fig. 5). In contrast, Norris et al. (1978) reported that porpoises reacted to tuna boats by tightening the group structure.

Levels of boat noise at the distances where bowheads reacted strongly (e.g. 200-1500 m) were quite high. However, caution must be exercised in comparing the noise characteristics of the various boats used or observed, given the sometimes imprecise estimates of range and the variable locations and water depths where their sounds were recorded. At a distance of 200 m, noise from the 'Adgo' was about 30-40 dB above low ambient levels and 10-20 dB above higher ambient levels for most frequencies below 500 Hz, and about 5-40 dB above ambient at 500-4000 Hz (Greene 1982: Figs. 5 and 6 vs. 8). If we assume that the 'Canmar Supplier IV' produces sounds at least as strong as those made by the 'Supplier VIII', we can make some statements about the sounds probably received by the whales that were disturbed by the 'IV'. 'Supplier VIII' is similar in size to 'Supplier IV', but has less powerful engines (2200 vs. 7200 shp) and a lower normal speed (19 vs. 26 km/h). Our recordings of the 'VIII' were made at an estimated range of 185 m. This is similar to the range at which the 'IV' passed the closest whales on 19 August 1980. The strongest sound of the 'VIII' (56 Hz) was received at about 121 dB//1 μPa, which was almost 10 dB greater than the strongest sound (113 dB at 90 Hz) recorded from the 'Adgo', a smaller vessel, at a similar range.

None of these vessels were nearly as noisy as the hopper dredge 'Geopotes X' when it was travelling. Indeed, at frequencies below 350 Hz, the noise level 7.4 km from the 'Geopotes X' was higher than that about 0.2 km from the 'Adgo' (Greene 1982: Fig. 8 vs. 17). Unfortunately we had no opportunities to study the behavior of bowheads near the 'Geopotes X' when it was travelling. It would be useful to know whether bowheads would react as strongly to the 'Geopotes X' at a range of 7.4 km as they do to the 'Adgo' at 0.2 km. In this regard it may be noteworthy that Watkins et al. (1981) mention that feeding by humpback whales was not disrupted by passage of a large oil tanker within 800 m. On the other hand, Jurasz and Jurasz (1979) believe that humpbacks are negatively affected by boat traffic, at least when exposure is repeated.

Our observations of reduced surface and dive durations during encounters with boats are generally consistent with previous accounts of the reactions of baleen whales to boats. Ray et al. (1978) reported that the mean surface and dive times of a fin whale being chased during a tagging operation decreased. The mean surface time dropped from 2.43 min to 0.87 min during the chase (which lasted 55 min) and to 0.81 min on the next day (13 h later). During the chase, when the whale was undoubtedly exerting itself very greatly, the down time was reduced by about half, from 6.33 min to 3.46 min. The next day the length of the down time increased to the pretreatment level, but the time at the surface remained at the same reduced level as during the chase. (However, Ray et al. carried out their aerial observations from a piston aircraft at an altitude of 152 m; thus the aircraft also may have influenced the whale's behavior.) The observations detailed by Ray et al. are consistent with the behavior of whales being chased by whale catcher boats, as described by Ommanney (1971). However, Jurasz and Jurasz (1979) noted that dive times increased when humpback whales were approached by vessels in Glacier Bay in southeast Alaska; surface times were not reported. In summary, in the presence of boats baleen whales consistently reduce their time at the surface per surfacing, but may either reduce or increase their average time below the surface per dive. Bowheads, like the fin whale observed by Ray et al., had reduced dive as well as reduced surface times when boats were nearby.

At least in 1980, the overt movement of bowheads away from moving boats did not begin until the boats were within 1 km. Thus, some of the bowheads that we observed exhibited some degree of tolerance of ship noise; they did not begin to move away from the noise source until the vessels approached quite closely. The noise was presumably audible to these whales well before they first began to move rapidly away. (This is demonstrated by the fact that surfacing and respiration patterns were altered subtly in response to an idling vessel 3-4 km away.) Other workers have also reported some degree of tolerance of boats by various baleen whales (e.g. Bogoslovskaya et al. 1981; Watkins et al. 1981), and even attraction to boats in certain cases (Winn and Perkins 1976; Dahlheim et al. 1981). Fraker (1977a) also concluded that white whales exhibited some tolerance of vessel sounds. However, white whales in shallow water responded at a range of about 2.4 km by moving away from barges pushed by tugs; this range is greater than the range observed for bowheads in our 1980 boat encounters, but similar to the range observed in 1981.

In summary, on at least some occasions, bowheads react to boats at distances of several kilometres when the boats are producing noise. When a boat approaches to within 1 km, and sometimes to within 3 km, the whales move away from the boat. However, we found no evidence that bowheads vacated any area where they had been disturbed by a boat; the 'flight' response seemed to be of brief duration. Whether frequent or continuous boat disturbance would ultimately cause bowheads to vacate an area or would lower their reproductive fitness is unknown.

Reactions of Bowheads to Aircraft

Whales that were circled by our Islander aircraft flying at an altitude of 305 m ASL usually dove (Table 6). We cannot analyze the response in any rigorous way, but the correlation between the presence of the aircraft circling overhead at 305 m and the whales' diving was clear to the observers. Bowheads only occasionally dove precipitously when overflown at an altitude of 457 m, and did not do so when overflown at 610 m. Comparison of observations from the Islander at various altitudes suggested that mean blow intervals and surface times sometimes were reduced slightly when the aircraft circled at lower (e.g., 305 m) altitudes.

This experience is consistent, in part, with LGL experience in circling bowheads in Twin Otter aircraft. The Twin Otter (300 series) is slightly larger than the Islander (wing span 20 vs. 16 m, length 16 vs. 11 m, gross weight 5700 vs. 3000 kg), but the most important difference may be that the Twin Otter has two small turboprop engines (PT6A series) whereas the Islander has two piston engines (Lycoming IO-540 series). On several days in August and September 1981, bowheads in the eastern Beaufort Sea were circled by a Twin Otter at altitudes of 457-610 m for purposes of behavioral observations (Davis et al. 1982). There was little evidence of reactions to the aircraft. When circled or overflown by a Twin Otter at 305 m, bowheads sometimes do dive precipitously (Fraker unpubl.). In the eastern Canadian arctic, bowheads overflown by a Twin Otter at 90 m almost always dove but those overflown at 150 m usually did not dive during the first pass (W.R. Koski, LGL Ltd., pers. comm.). Ljungblad et al. (1980) and Ljungblad (1981) found indications that sensitivity to aircraft varied with location, season or both.

The above experience suggests that bowheads are more sensitive to aircraft than are at least some other baleen whales. Watkins and Schevill (1976, 1979) reported good success in observing the apparently undisturbed behavior of right, humpback, sei and fin whales from small, single (piston) engine aircraft at altitudes of 50-300 m. During detailed studies of the southern right whale, R. Payne (New York Zoological Society, pers. comm.) has found that a light aircraft with a single engine (piston) disturbs very few individuals when it is flown above 100 m. Payne had an independent check on the effects of the aircraft from observations made from shore.

Most of the response of bowheads may be attributable to aircraft sound that is transmitted from the air into the water. Urick (1972) indicates that this transfer can take place under some circumstances with a loss of only 7 dB. In this study we found that, at least on near-calm days, considerable aircraft sound entered the water and was received by our hydrophone when we measured the sounds of the Islander, a Twin Otter, and a Bell 212 helicopter (Greene 1982).

In the case of the Islander aircraft, tonal sounds at frequencies corresponding to the propeller blade and cylinder firing rates were prominent in the received spectrum. Levels received at the hydrophone were as high as 102 dB//1 μPa at 70 Hz, averaged over the 4-s period of most intense sound; this and sounds at other low (<1000 Hz) frequencies were 10-30 dB//1 μPa^2/Hz above quiet ambient levels (Greene 1982: Fig. 5 vs. 18-20). As aircraft altitude increased, there was a decrease in the noise level during the 1 s period with maximum aircraft noise. However, aircraft noise was detectable for a longer period when the altitude was high than when it was low. In part because of these two factors, the average levels recorded over 4 s or 8 s periods were rather similar for all altitudes in the 152-610 m range--92 to 102 dB//1 μPa for the 70 Hz tone (Greene 1982). The more pronounced reaction of bowheads to the Islander when it was at low altitude might be a function of the higher peak level when the aircraft is low, or of the more sudden onset of the peak noise, or perhaps a combination of the two.

Broadband sound levels from the Twin Otter were similar to those from the Islander at low frequencies (<150 Hz). Above 150 Hz, broadband levels from the Twin Otter were typically a few dB higher than those from the

Islander. The tonals were at different specific frequencies, and the strongest tone from the Twin Otter was more intense than the strongest tone from the Islander (Greene 1982). Spectrographic analysis showed that the spectrum of the Twin Otter was more stable from moment to moment than was the spectrum of the Islander (Greene 1982: Fig. 20 vs. 22).

Unfortunately, we were not able to observe the reactions of bowheads to helicopters, which are the types of aircraft involved in most of the offshore flying in support of oil and gas exploration and development. However, our recordings of noise from a Bell 212 helicopter showed that its noise was considerably more intense than was the noise from either the Islander or the Twin Otter (Greene 1982). This was true across all frequencies analyzed, with the exception of a few tonals. The strongest recorded tone was at about 20 Hz, and was probably attributable to the main rotor. The 20 Hz tone was no stronger than the strongest tone in the spectrum of the Twin Otter. However, many more tones were present in the helicopter noise spectrum than in the Twin Otter spectrum. These results suggest that bowheads would react more strongly to a helicopter such as a Bell 212 than they do to fixed-wing aircraft. However, it is noteworthy that during five flyovers at 152-610 m ASL and 185 km/h, the helicopter noise was only audible on our tape for 16-27 s per pass (Greene 1982). Thus bowheads would not be subjected to intense noise for a prolonged period when a helicopter makes a single pass overhead.

Reactions of Bowheads to Seismic Exploration Noise

The impulsive sounds from seismic exploration are by far the most intense sounds in the Beaufort Sea, although each impulse is of short duration. Thus it was of special importance to examine the behavior of bowheads in the presence of seismic signals, and to determine whether bowheads tend to avoid the areas around the ships that create these impulses.

On two occasions we observed the behavior of bowheads near an active seismic ship. On these occasions, at distances of 13 km and 6-8 km from the ship, there was no clear evidence that behavior was disrupted or that the whales were leaving the area. It is possible that surfacing and respiration characteristics were slightly altered, but the evidence was inconclusive.

Received noise levels at these distances were about 141 and 150 dB, respectively. Bowhead calls were recorded on the latter occasion, and bowhead calls were also recorded in the presence of distant seismic noise on several other days (Würsig et al. 1982: Table 5). Industry personnel report that bowheads sometimes approach considerably closer to seismic ships than we have observed (see Results).

In general, uncontrolled observations of bowhead behavior 6-8 km or more from full-scale seismic operations revealed no clear effect on the whales. However, these observations must be treated with caution because we have no data from situations that differed only by the absence of seismic noise. While there was no conclusive evidence that surfacing and respiration behavior was unusual in the presence of full-scale seismic noise, there were some differences from behavior during the most closely comparable 'undisturbed' conditions. These differences may or may not have been attributable to the seismic operations.

The results from our two airgun experiments are more readily interpreted, because in those cases pre- and post-airgun observations of the same whales were obtained. In the 18 August 1981 trial involving whales that were echelon feeding 5 km from the airgun, there were clear effects on surfacing, respiration and calling behavior and possibly on group size. However, the whales remained in the area and continued to feed during the period of airgun noise. During the 19 August 1981 trial only 3 km from the airgun, we detected no statistically significant effects, although trends in surfacing and respiration behavior during the pre-airgun, airgun and post-airgun phases were similar to those on 18 August (Fig. 11).

The lesser apparent effect when the airgun was 3 km away than when it was 5 km away was unexpected. Possibly the whales were less sensitive to the noise in the 3 km trial. At least two reasons for reduced sensitivity in the 3 km experiment can be suggested, but the first of these can be discounted. (1) Their behavior during the pre-airgun phases of the two experiments was very different: the whales were feeding just below the surface in highly organized echelons before and during the 5 km trial, but were diving deeply before and during the 3 km trial. If the depth of dives were the determining factor, then one would have expected a stronger, not a weaker, response in the 3 km trial. Because of the pressure release phenomenon at the surface, low-frequency sounds are received more strongly at mid-water depths than near the surface at the same horizontal range. (2) Another possibility is that habituation had occurred. The 3 km experiment was done at the same location (within 1 km) as the 5 km experiment, and only 18.5 h later. The whales observed in the 3 km experiment may well have been nearby during the preceding 5 km experiment.

The apparent difference between our results 5 km from the airgun and 8-13 km from full-scale seismic ships is also consistent with the possibility that habituation occurs. Clear reactions to the airgun at 5 km range were evident, whereas there was little evidence of reaction to the full-scale seismic ship at 8 or 13 km. We are confident that sound levels 5 km from the one airgun were less than those 8 and even 13 km from the seismic ship, but we have no precise information on this point. We suspect that the reactions to the 20 min period of airgun noise were at least partly in response to the start-up of a novel stimulus. The whales observed near the seismic ship had presumably been subjected to intense noise for a considerable period before our observations began. It is possible that their behavior was more seriously affected before we began to observe.

In considering the apparent tolerance by these whales of the presence of intense seismic exploration sounds, it may be important to consider the levels of sounds to which the bowheads might be exposed naturally. One probable source of loud sounds is the bowhead itself, and other bowheads. Intensity levels for bowhead whale sounds have been estimated to be between 135 and 145 dB//1 µPa at 100 m (Clark and Johnson in prep.), which translates to source levels of 175-185 dB at 1 m assuming spherical spreading. These estimates are similar to those estimated (Cummings et al. 1972, 172-187 dB) and measured (Clark, unpubl., 181-186 dB) for the closely related southern right whale. Buck and Greene (1979) also reported that sounds up to 200 Hz associated with ice pressure ridge activity were produced over several minutes with source levels as high as 136 dB.

The fact that baleen whales 'tolerate' loud sounds produced by ice, by themselves or by conspecifics indicates that they can tolerate certain very loud noises. However, this speculation cannot be extended to conclude that any such capacity is unlimited, or to conclude that there is no concern about the possible masking of important environmental or communication sounds by industrial noise.

One must be very cautious in interpreting our few observations of bowheads in the presence of full-scale seismic exploration sounds, since it was not possible to make before- or after-disturbance 'control' observations, and since we did not observe the behavior of these animals when they were first exposed to the noise. We found detectable changes in bowhead behavior when a single airgun with source level about 222 dB//1 µPa began to fire 5 km away. A full-scale airgun array can have a source level of about 248 dB (Ljungblad et al. 1980; Johnston and Cain 1981). Its signals at 19.5 km range would equal those of our one airgun at 5 km, assuming that propagation loss rates equal those of seismic signals studied by Greene (1982:Table 4). Thus, detectable changes in bowhead behavior might sometimes occur at distances of 20 km or more from full-scale seismic operations, at least when they first begin after a period without seismic signals. In deep water, where propagation losses would probably be less rapid than in our study area, the 'start up' effect might occur at even greater ranges.

Presence of Bowheads near Drillships

Drilling in the Alaskan Beaufort Sea will be from artificial and natural islands, at least initially. Unfortunately, drilling from artificial islands was not in progress in our study area during our two field seasons. Thus we could not observe the reactions of bowheads to such an operation, nor could we record the noise emanating into the water. Measurements of waterborne drilling noise from islands in the Alaskan Beaufort Sea in winter indicate that the sound does not propagate very far (Malme and Mlawski 1979). However, this result does not necessarily apply in the open-water season, when propagation conditions are different and when bowheads are present. Propagation is also likely to be better from islands in deeper water.

In 1980, industry personnel reported several sightings of bowheads at estimated distances of 0.2 to 5 km from drillships. In 1981, we found that bowheads were present for several days 8-20 km from a drillship, and on one occasion we observed three whales, including a yearling, only 4 km from the ship. Curiously, the blows per surfacing and dive time values 4 km from the ship were greater than normal, and greater than those of another group of whales 15 km from the drillship. (In the cases of boat and airgun disturbance, these values are reduced, not increased.) However, in the absence of control data from the same individual whales, no detailed analysis is possible.

The drillship near which our observations were made produced considerable noise while drilling. The strongest tonal sound was at about 278 Hz. Its levels at distances of 1, 4 and 8 km were about 121, 111 and 102 dB//1 μPa (Greene 1982), and a relatively strong tonal believed to be from this drillship was detected at a range of 13 km on one occasion. In contrast, Malme and Mlawski (1979) observed low frequency tones from a drilling operation on an icebound island to ranges of 6.4-9.6 km under low ambient noise conditions, and to only about 1.6 km under high noise conditions.

Our observations show some degree of tolerance of drillship operations but the meagre and uncontrolled data are at best preliminary. It is also uncertain how relevant these observations near drillships may be to the question of bowhead reactions to drilling on islands. Propagation of sound from these two types of drilling operations into the water probably is quite different. Also, buoy tenders and other boats are often active around drillships, so boat noise (additional to drillship noise) is likely to be more frequent near a drillship than near a drilling site on an island. It would be desirable to obtain measurements of drilling noise propagation from islands in open water, and to observe the reactions of bowheads to a real or simulated operation of that type.

Presence of Bowheads Near Artificial Island Construction

A substantial number of bowheads were present near Issungnak artificial island in August 1980 (Table 11; Figs. 12, 13). Most of the whales were north of the 18-m isobath, which extends approximately east-west past Issungnak. During aerial surveys, several whales were seen within 5 km of the island and 2 were within 0.8 km. Workers in the Issungnak area reported several observations of bowheads; one bowhead was reportedly only 16 m from the barge camp (Table 12).

The recordings of composite sounds produced by the dredge and auxiliary equipment (barge camp, tugs, etc.) show that the sounds in the Issungnak area were well above quiet ambient levels out to a range of at least 4.6 km north of the dredge, especially at frequencies below 2000 Hz (Greene 1982: Fig. 33). Comparison of received sound levels at various distances indicated that propagation of the construction noises, at least to the north into deeper water, was quite good. The sounds received at 4.6 km from the dredge were 10-20 dB higher for frequencies below 8000 Hz than the sounds received 3.7 km from the 'Imperial Adgo' when her engines were idling. Because bowheads appeared to respond to the less intense sounds from the 'Adgo', it seems certain that the sounds from the island construction operation were audible to bowheads within 5 km of Issungnak, and--at least to the north where the water was deeper--probably for some considerable distance beyond that. Measurements of the same dredge at Alerk Island in 1981 show that considerable noise propagated to a range of 7.4 km in the somewhat shallower water in that area (Greene 1982: Fig. 37).

Given the uneven and apparently depth-dependent distribution of bowheads in the general area around Issungnak (Figs. 12, 13), there were too few sightings during the surveys to determine conclusively whether there was any tendency for fewer bowheads to occur there than in other similar areas. The decrease in abundance of bowheads near Issungnak in the latter half of August 1980 probably reflected a general eastward shift in bowhead distribution at that time (see Renaud and Davis 1981; Würsig et al. 1982) rather than any direct reaction to disturbance.

The presence of numerous bowheads in the Issungnak area in 1980 was surprising. Fraker (1978) and Fraker and Fraker (1979) conducted surveys in this area in 1978 and 1979. These surveys were similar to those conducted in the present study except that the spacing between survey lines was 9.6 km (instead of 3.2 km), and the surveys extended somewhat farther east, west and north (to 64 km offshore). Surveys were flown on 26 and 29 July and 2 and 8 August in 1978, and on 21 July and 2 and 8 August in 1979. During these surveys there were only 3 observations of a total of 5 bowheads in 1978 and 1 observation of a single bowhead on 8 August 1979. Considering only the August surveys, the recorded densities of bowheads were 0.00045, 0.00045 and 0.038 whales/km2 in 1978, 1979 and 1980, respectively. Industry personnel reported 8 sightings of a total of 63 whales in 1978, only 2 sightings of a total of 7 individuals in 1979, and 18 sightings of 136 individuals in 1980 (Table 12*). These results suggest that there were major differences in distribution among years.

In 1981, few bowheads approached the Issungnak area. From about 18 to 25 August we found bowheads within 25 km to the west or southwest. However, on other dates in 1981 few or none were seen near Issungnak, and we never saw bowheads near the dredging operation at Alerk in 1981. Systematic surveys of the entire southeastern Beaufort Sea were conducted from late July to early September 1981 (Davis et al. 1982), and they--like the present study--showed that bowhead distribution was quite different from that in 1980. It is not known whether this had any connection with the industrial activity in the area where bowheads were so numerous in 1980. However, relative to numbers present near Issungnak in 1980, bowheads were much less numerous there in 1978-79 as well as in 1981. Thus, year-to-year fluctuations in the summer distribution of bowheads may be common irrespective of industrial activities.

Concluding Remarks

This study was designed to determine, by experimental and observational approaches, the immediate behavioral reactions of bowheads to potential sources of disturbance. Unambiguous behavioral reactions were found to each of the types of potential disturbance that we presented to bowheads (boats, aircraft at low altitude, airgun noise). Each of these incidents involved the introduction of a type of disturbance to which the animals had not been exposed in previous hours. We have not yet been able to test the reactions of bowheads to start-up of a dredge or drilling operation, but we observed some degree of tolerance to ongoing seismic exploration, dredging and drillship operations. All of these activities produce considerable

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* Table 12 lists only sightings made in the Issungnak area and, in contrast to the data for 1978 and 1979, omits additional sightings made elsewhere, thus under-reporting the 1980 results. Where the number of bowheads in a sighting was given a range (e.g., 20-30), the smaller number was used.

underwater noise (Greene 1982). Indeed, the airgun to which reactions were observed probably produced less noise at the whales' location than did full-scale seismic exploration, to which no unambiguous reactions were found. Bowheads swam rapidly away from approaching boats for a brief period, but there was no evidence that bowheads moved out of the general area in the minutes or hours following any of the above types of short- or longer-term disturbance.

Our observations to date suggest that bowheads are quite sensitive to novel types of disturbance, but soon habituate to some degree. After initial exposure and habituation, they apparently tolerate some industrial activities that produce quite intense sounds. Our data suggest that this tolerance extends over periods of at least several hours in the case of seismic noise, and probably for at least a few days in the case of distant dredging or drilling sounds. To further determine whether habituation is an important factor in this tolerance of dredging and drilling noise, it will be important to perform controlled tests of the reactions of bowheads at the onset of such operations.

We have no direct information about the longer term effects of offshore industrial operations, or of repeated encounters with boats or aircraft. Long term effects are much less amenable to study than are immediate behavioral responses. One could argue that the effects must not be too severe because bowheads continue to return to the southeastern Beaufort Sea each summer despite offshore seismic exploration there for many years, artificial island construction for a decade, and drillship operations for six years. A further indication of their long-term tolerance of disturbance is the fact that they continue to migrate each year through the Alaskan waters where some individuals are chased by hunters, and in some cases wounded or killed. On the other hand, one must question whether the demonstrated year-to-year variability in bowhead distribution and movements within the southeastern Beaufort Sea region over the 1978-81 period has any connection with the intense offshore industrial activity in that region during that period.

Whether or not bowhead distribution has been affected by offshore oil and gas exploration so far, the fact that some bowheads 'tolerate' the disturbance over a prolonged period does not prove that they are unaffected. Studies in other types of mammals suggest that stress-inducing factors may have important physiological and population effects (Christian 1971; Selye 1973; Geraci and St. Aubin 1980). A brief behavioral study on free-ranging animals can provide important information about short- and medium-term behavioral reactions, but it cannot address questions about long-term or physiological effects. Unfortunately, even in mammal species that are more amenable to study, stress effects at the population level are poorly documented.

There are other approaches that would be useful as a supplement to the behavioral approach that we have emphasized to date. The fact that many bowheads are individually recognizable via distinctive natural markings (Davis et al. 1982; Würsig et al. 1982) provides one as yet unused tool for long-term studies of reactions of individual bowheads to disturbance. We have now started to accumulate information about the locations, companions and behavior of specific individuals at specific times. Radio telemetry would permit tests of the reactions of an individual to repeated aircraft or boat disturbance. When sufficiently refined, radio telemetry might also provide the means for recording certain physiological data on a long-term basis on free-ranging bowheads that were subjected to disturbance. The latter technique has recently been employed to advantage in studies of the reactions of terrestrial mammals to disturbance (e.g., MacArthur et al. 1979).

There has been much recent concern about the possibility that noise from offshore industrial operations will interfere with acoustic communication among bowheads (e.g. Peterson [ed.] 1981). In deep waters of the eastern Canadian arctic, intense ship noise or other continuous sounds may propagate very long distances and could mask bowhead communications within a large area (Møhl 1981; Terhune 1981). In the shallow waters of the southern Beaufort Sea industrial noise may not be as severe a problem because of the more rapid attenuation with increasing distance. Nonetheless, masking could occur within certain areas. Furthermore, we have already found indications that bowheads reduce their rate of calling in the presence of industrial noise (C.W. Clark, in Würsig et al. 1982; also see airgun results above). Most bowhead sounds are at frequencies below 1000 Hz, and especially at frequencies of about 75 to 400 Hz. This is also the band containing most of the more intense industrial sounds (Fig. 15).

These considerations suggest that an understanding of the importance of various types of bowhead sounds is critical for an assessment of the long-term effects of offshore industrial operations on bowheads. We and others have documented the various types of bowhead sounds, and we have begun to learn their contexts and possible functions (Würsig et al. 1982). However, our understanding of the latter topic is still rudimentary because of the difficulty in associating particular recorded bowhead sounds with particular animals whose behavior is under observation. This line of study is also one that should be pursued.

The question of the applicability of our results to Alaskan waters has been raised. Our data were obtained in the southeastern Canadian Beaufort Sea in August and early September, when bowheads are feeding, socializing and, on an intermittent basis, travelling considerable distances. The behavior of bowheads in the Alaskan Beaufort Sea in September and October appears very similar (Braham et al. 1977; Ljungblad et al. 1980; Lowry and Burns 1980; Ljungblad 1981 and pers. comm.; LGL Ltd. unpubl.). It is incorrect to say that bowheads feed in summer and migrate in autumn; they do both in both seasons. Furthermore, some of our results, especially with regard to aircraft disturbance, were obtained in early September near Herschel Island, Y.T., which is only 75 km from the Alaskan border. Although corroborative studies in Alaska in autumn would be desirable, we consider it unlikely that reactions there will differ appreciably from those described in this report.

The applicability of our results to the winter and spring migration periods is less certain. Movements of bowheads and propagation of sounds are affected by ice at those seasons. This may affect the reactions of bowheads. Despite the logistical difficulties, studies in those seasons would be desirable with regard to potential offshore industrial activities that may occur in the Bering Sea in winter or along the spring migration route in the Bering, Chukchi or Beaufort seas.

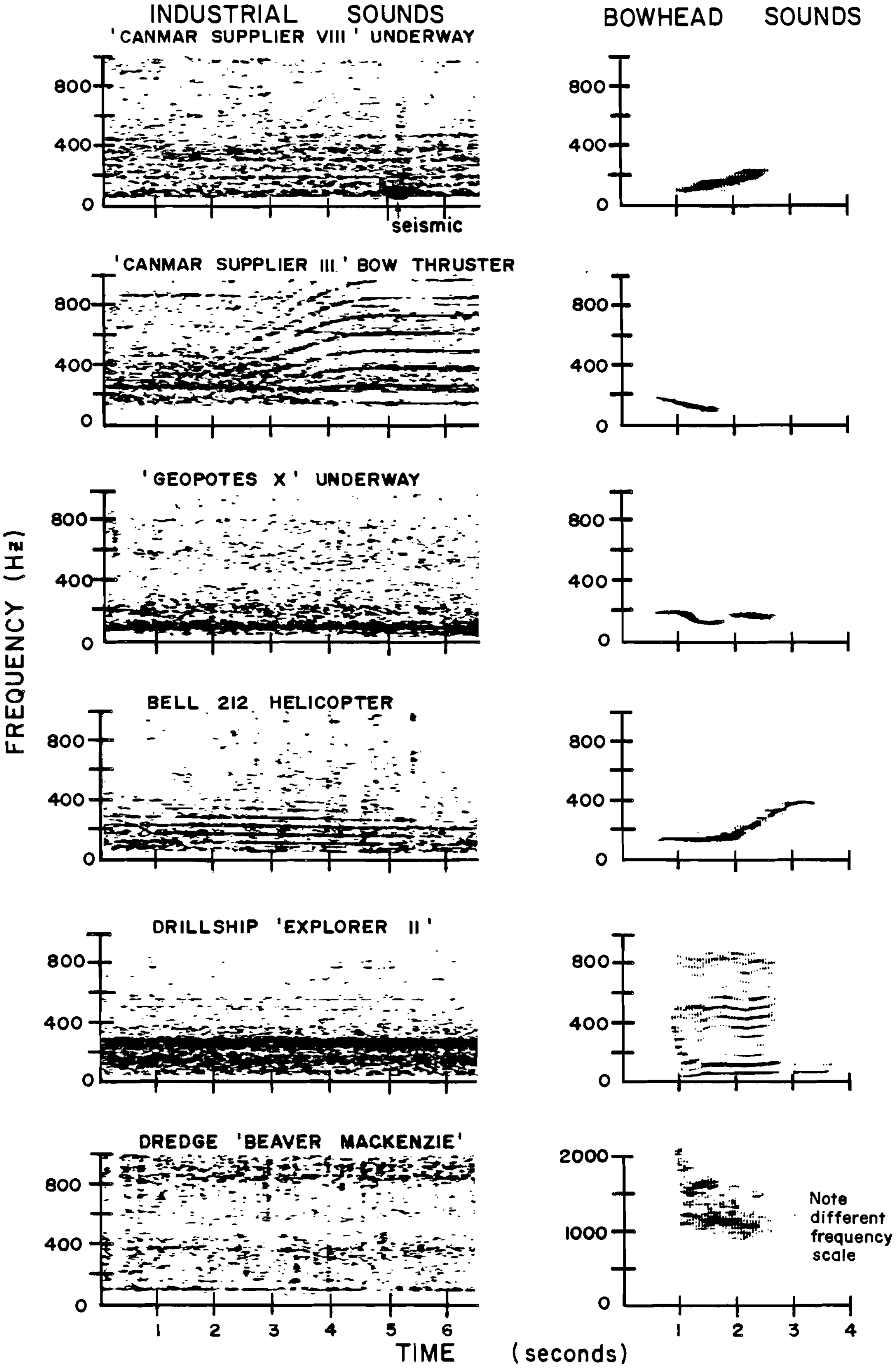

FIGURE 15. Spectrograms of industrial sounds (left) and bowhead sounds (right) recorded in the eastern Beaufort Sea, 1980-81. Spectrograms are by C.W. Clark. See Greene (1982) and Würsig et al. (1982) for more details.

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Appendix 1. Orientations of bowhead whales observed from the 'Imperial Adgo' on 23, 24, 26 and 27 August 1980. The whales' orientation in relation to the boat was recorded with respect to the face of a clock: 6 o'clock = toward the boat, 12 o'clock = away from the boat, etc.; see 'Methods' and Figure 2 for more details. Each individual or group was tallied only once for each surfacing.

	Orientations (categories)							
Conditions	12 (1)	11+1 (2)	10+2 (3)	9+3 (4)	8+4 (5)	7+5 (6)	6 (7)	Total
Engines off	23	23	39	54	42	16	24	221
>900 m	4	2	5	9	14	6	4	
≤900 m	19	21	34	45	28	10	20	
Engines idling	21	15	32	22	11	9	3	113
>900 m	5	9	6	5	1	1	0	
≤900 m	16	6	26	17	10	8	3	
Engines engaged	38	17	25	10	4	0	1	95
>900 m	2	4	5	2	3	0	0	
≤ 900 m	36	13	20	8	1	0	1	

Appendix 2. Surfacing, respiration and dive characteristics of bowhead whales observed near the seismic vessel 'Arctic Surveyor' and the MV 'Sequel' on 25 August 1981. The 'Arctic Surveyor' was actively shooting throughout the entire observation period.

Disturbance Category	Mean	s.d.	n
BLOW INTERVALS DURING			
seismic	11.0 s	5.26 s	109
'Sequel' plus seismic	14.0	9.78	30
post-'Sequel' plus seismic	10.3	6.10	51
SURFACE TIMES DURING			
seismic	51.8 s	37.78 s	31
'Sequel' plus seismic	24.6	35.50	25
post-'Sequel' plus seismic	44.5	32.91	16
BLOWS/SURFACING DURING			
seismic	4.0	3.68	25
'Sequel' plus seismic	2.0	2.14	24
post-'Sequel' plus seismic	3.8	3.49	14
DIVE TIMES DURING			
seismic	318.5 s	296.1 s	8
'Sequel' plus seismic	13.8	4.5	9
post-'Sequel' plus seismic	162.5	227.0	2

Appendix 3. Surfacing, respiration and dive characteristics of bowheads observed from the Britten-Norman Islander at altitudes 1500-1900 ft vs. 2000-2800 ft during 1980-1981.

Year	Altitude (ft)	Mean	s.d.	n
Blow Interval				
1980	1500-1900*	12.571 s	6.235 s	231
	2000-2800**	13.016	9.148	703
1981	1500-1900	13.178	9.674	594
	2000-2800	12.795	6.255	533
Both	1500-1900	13.008	8.848	825
	2000-2800	12.921	8.027	1236
Blows/Surfacing				
1980	1500-1900	5.750	2.137	12
	2000-2800	4.732	2.882	56
1981	1500-1900	3.678	2.657	118
	2000-2800	4.333	3.198	84
Both	1500-1900	3.87	2.675	130
	2000-2800	4.49	3.071	140
Surface Time				
1980	1500-1900	79.792 s	31.500 s	24
	2000-2800	73.250	57.082	76
1981	1500-1900	55.048	44.844	126
	2000-2800	68.763	43.273	93
Both	1500-1900	59.01	43.853	150
	2000-2800	70.78	49.851	169
Dive Time				
1980	1500-1900	261.8 s	290.6 s	4
	2000-2800	115.4	193.2	24
1981	1500-1900	177.3	244.1	55
	2000-2800	240.3	331.9	29
Both	1500-1900	183.0	245.6	59
	2000-2800	183.7	282.4	53

* 457-580 m ** 610-854 m.

Appendix 4. Surfacing, respiration and dive characteristics of bowhead whales observed from the Britten-Norman Islander at different altitudes on 6 and 8 September 1981.

Variable	Altitude (m)	Mean	s.d.	n
6 SEPTEMBER 1981				
Blow Interval	610	13.16 s	4.392 s	81
	457	11.80	3.753	25
	305	10.45	4.489	20
Surface Time	610	42.27 s	49.46 s	11
	457	28.50	21.92	2
	305	46.00	36.77	2
Blows/Surfacing	610	2.82	2.926	11
	457	2.50	2.121	2
	305	2.00	-	1
Dive Time	610	239.3 s	404.1 s	3
	457	6.0	-	1
	305	-	-	0
8 SEPTEMBER 1981				
Blow Interval	610	10.92 s	3.167 s	104
	305	9.55	2.849	44
Surface Time	610	80.50 s	40.675 s	12
	305	48.50	26.599	6
Blows/Surfacing	610	6.64	3.529	11
	305	5.00	1.414	4
Dive Time	610	39.5 s	24.365 s	4
	305	-	-	0

Appendix 5. Surfacing, respiration and dive characteristics of bowheads observed before, during and after an airgun was discharged at a distance of 5 km (18 Aug 1981) or 2.5-3.5 km (19 Aug 1981).

	Mean	s.d.	n
Blow Interval (s)			
18 August - Control	15.800	15.362	70
- Airgun	16.083	7.077	12
- Post-airgun	17.194	8.908	31
19 August - Control	13.391	12.910	138
- Airgun	13.429	8.441	21
-Post-airgun	12.000	5.164	10
Blows/Surfacing			
18 August - Control	3.227	2.159	22
- Airgun	0.833	0.753	6
- Post-airgun	2.692	2.359	13
19 August - Control	4.069	3.046	29
- Airgun	3.111	1.691	9
- Post-airgun	4.000	2.646	3
Surface Time (s)			
18 August - Control	49.043	49.711	23
- Airgun	11.667	11.928	6
- Post-airgun	58.538	42.396	13
19 August - Control	63.805	39.200	41
- Airgun	46.667	20.603	9
- Post-airgun	60.600	34.288	15
Dive Time (s)			
18 August - Control	139.89	221.55	9
- Airgun	68.60	54.85	5
- Post-airgun	147.73	220.20	11
19 August - Control	202.60	358.86	5
- Airgun	-	-	0
- Post-airgun	403.00	395.47	4

Appendix 6. Behavior of one recognizable whale during the airgun experiment on 18 August 1981.

Although one must recognize the limitations of interpretation that are inherent in examining the behavior of one or a few whales, it is of some use to describe detailed observations made on 18 August 1981. Except for brief intervals, we were able to follow the behavior of a large whale with a distinctively marked tail peduncle for nearly 3 h (from 18:38 to 21:25). The track of this whale is shown in Fig. 16. It is important to recognize that the track line is based on time rather than actual distance. The lengths of the lines in the figure represent times spent on various headings at relatively slow or fast swimming speeds. The usefulness of this figure is to demonstrate the pattern of movement of a whale engaged in skim feeding in echelon formation before, during and after being exposed to the sounds of the airgun. The details of the whale's behavior are outlined below (letters refer to segments of the whale's track shown on Fig. 16):

Pre-Airgun Phase

(a) The large whale with the white peduncle (WP) swims slowly north, leading an echelon containing two other whales, all sub-surface skim feeding. Several other echelons are nearby, moving in different directions. 'Sequel' is moving north slowly at a range of 5 km to the west of the whales.

(b) The echelon containing WP passes one body length ahead of an 11-whale echelon; all but two whales have their mouths open. One whale of the 11 joins WP's echelon.

(c) WP's echelon hangs at the surface. WP and one other smaller whale roll onto their sides and right themselves. The smaller whale is touched by a third, which then moves between WP and the smaller whale.

(d) WP joins a new echelon consisting of three whales. The echelon formation breaks down. WP moves into the lead position as the echelon reforms. One whale rolls, ventrum up, as they hang at the surface. The smaller whale from WP's previous echelon rejoins WP. WP is now in the lead of an echelon of six whales.

(e) Another whale joins the echelon from the left.

(f) WP hangs at surface. One whale places its chin on WP's back, then slides off. The other whales engage in rolling and mixing as the formation breaks down. WP swims off by itself.

(g) We briefly lose track of WP as it swims deeper and out of sight. The closest whale is 15 body lengths away.

(h) WP enters an area where five echelons are moving roughly at right angles to each other.

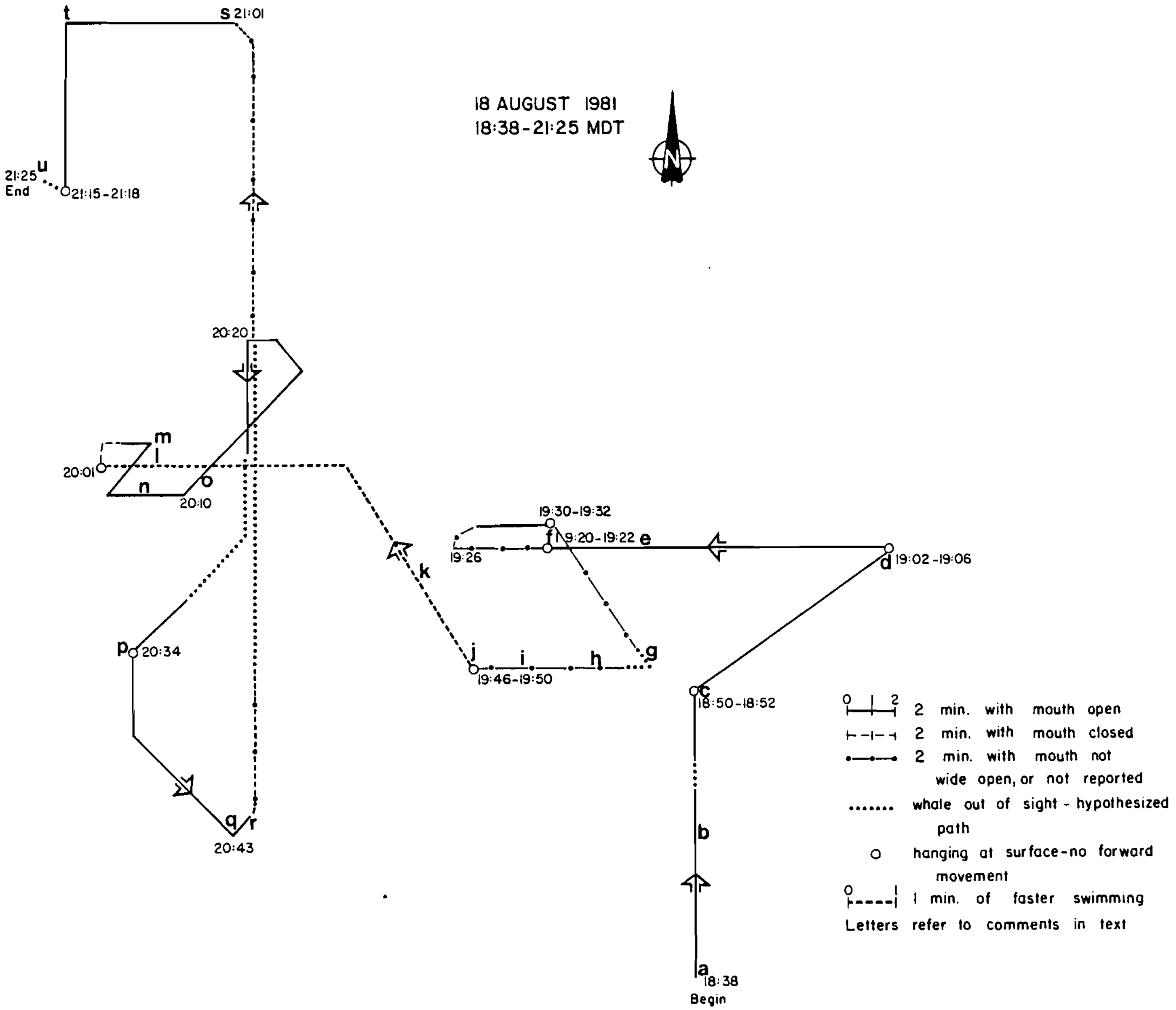

FIGURE 16. Diagrammatic representation of the path of an identifiable bowhead observed before, during and after an airgun was discharged 5 km away on 18 August 1981. Airgun was discharged from 19:49 to 20:09 MDT.

Appendix 6. Continued.

(i) Two whales approach WP. WP hangs at surface.

Airgun Phase

(j) 'Sequel' begins firing its airgun at a range of 5 km to the south at 19:49 MDT.

(k) An echelon of four whales is six body lengths from WP. WP moves at medium speed; all whales are sub-surface skim feeding.

(l) WP passes another whale 2 ½ body lengths away without any overt interaction. At least one other (smaller) whale is with WP.

(m) WP and an approaching whale turn to avoid colliding.

(n) WP leads an echelon of five whales that is joined by three more. The airgun experiment ends at 20:09 MDT, with 'Sequel' approximately 4 km to the south.

Post-Airgun Phase

(o) WP leads three smaller whales as a group of four breaks off from the echelon.

(p) WP is leading two others in an echelon while sub-surface skim feeding. WP stops as it blows, then continues moving slowly with mouth open.

(q) The other two whales leave WP. 'Sequel' is 5 km at 220°T from the whales.

(r) WP is moving more rapidly, alone.

(s) WP leads an echelon of three whales, all with mouths open.

(t) WP turns southward, moving slowly and alone; mud is streaming from its mouth.

(u) WP is resighted, and is once again sub-surface skim feeding.

Unfortunately we do not know how fast this whale swam while it was echelon feeding. The average speed of whales observed from the Herschel Island transit site was 5.1 km/h (Würsig et al. 1982). If we assume that WP swam at about ½ this speed (2.5 km/h) during the slow swimming periods while feeding, then the straight line distance between the start of our observations (point a) to the greatest distance from it (point t) represents about 2.0 km.

The frequency with which WP was the leader of echelons is noteworthy, but the data are too few to draw any conclusions about this behavior at this time.

Appendix 7. Surfacing, respiration and dive characteristics of bowheads observed 15 km and 4 km west of the drillship 'Explorer II' on 23 August 1981. The 15 km data were recorded from 18:15 to 19:17 MDT from several whales; the 4 km data were recorded from 19:34 to 20:20 from only two or three whales.

Variable	Distance	Mean	s.d.	n
Blow Interval	15 km	12.40 s	5.67 s	65
	4 km	11.98	4.39	62
Blows/Surfacing	15 km	3.77	4.40	17
	4 km	8.38	3.20	8
Surface Time	15 km	50.21 s	56.01 s	19
	4 km	89.50	30.21	8
Dive Time	15 km	28.3 s	32.65 s	11
	4 km	675.8	289.28	5

CHARACTERISTICS OF
WATERBORNE INDUSTRIAL NOISE *

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ABSTRACT

The primary goal of the overall project was to learn about the behavior of bowhead whales when subjected to the sounds and other stimuli associated with exploration for and development of offshore hydrocarbon deposits. An important objective was to study such sounds to determine their characteristics and how they attenuate with distance from a source. This section of the report contains the results of that study.

All work was in the open water of the eastern Beaufort Sea generally north of Tuktoyaktuk during August of 1980 and 1981. The shallow water varied in depth between 11 and 50 m. Measured salinity-temperature-depth data yielded profiles of the sound speed vs. depth. Sound speed was relatively constant from the surface to 8 or 10 m, decreased steeply from there to about 20 m, and was then constant to the bottom. Such a sound speed structure in such shallow water assures that sound will travel via downward refracted rays that bounce repeatedly between the surface and the bottom. Higher frequencies will be scattered and absorbed, and lower frequencies will not propagate significantly in the shallow water.

Our results are presented in four main ways: (1) averaged power spectra to describe the average characteristics of industrial machinery sounds, (2) spectrograms to describe the temporal behavior of industrial machinery sounds, (3) pressure-time waveforms to describe seismic survey sounds, and (4) equations for received level vs. range to describe the propagation of important components of sounds from in-water sources.

The ships and boats whose sounds were studied were a sea-going hopper dredge, two small supply ships, a personnel support boat, and the fishing boat used to collect many of the sound data. The hopper dredge 'Geopotes X',

136 m in length and displacing 17,981 tons, radiated the strongest signal component, a tone varying in frequency between 70 and 92 Hz. The received level was 138.2 dB//1 µPa at 460 m and is predicted to be 146 dB at 100 m, based on a regression equation relating received level to range; this equation was derived from measurements at ranges between 0.46 and 7.4 km. The dominant tone from a supply ship underway was at 56 Hz. It was measured at an estimated range of 185 m as 121 dB//1 µPa, and would be expected (based on regression estimates for other sounds) to be about 124 dB//1 µPa at 100 m. The bow thruster on another supply ship measured at 185 m radiated a strong harmonic family of tones whose fundamental frequency was at 118 Hz and whose strongest member was the second harmonic with an expected level at 100 m of 132 dB//1 µPa. The highest frequency tone found consistently was at 1000 Hz and came from the hopper dredge; its level at 100 m would be expected to be 130 dB//1 µPa.

The fundamental propeller blade-rate from a Britten-Norman Islander twin-engine aircraft at 152 m ASL (500 ft) occurred at 70 Hz at a level of 100-102 dB//1 µPa, measured at 18 m depth and averaged over 4 s. The strongest tone from a deHavilland Twin Otter at 152 m occurred at 82 Hz at a level of 104-110 dB//1 µPa, also averaged over 4 s but measured at 9 m depth. The strongest recorded tone from a Bell 212 twin-turbine helicopter occurred at 22 Hz at a level of 109 dB//1 µPa, measured at 9 m depth and averaged over 4 s. During the 1 s period of peak noise, the overall broadband helicopter sound was more intense than that from the two fixed-wing aircraft, and the level decreased with increasing altitude. However, when averaged over 8 s or 4 s, aircraft noise was not closely related to altitude. When the Twin Otter or Bell 212 helicopter flew over a hydrophone in water 22.5-25 m deep under low sea state conditions, the aircraft sound was audible for 16-37 s, depending on aircraft type and altitude.

In terms of intensity, the sleeve exploder signals from a seismic survey ship were much stronger than any other sounds examined in this study. They consisted of a series of high intensity pulses separated by several seconds. The length of the signal was 250 ms when received at 8 km and 400 ms at 28.7 km. The effect of the sound transmission properties existing during the measurements (which were typical for the place and season) was to stretch the signal from the impulse present at the source into a chirp-like signal descending in frequency at ranges beyond about 5 km. Signatures from an airgun were chirp-like at 5 but not at 3 km. A regression equation for received level of the sleeve exploder signals vs. range, derived from the measured signatures at 8-28.7 km (R2 = 0.97, n = 12), predicts a level of 180 dB//1 µPa at 100 m for frequencies near 150 Hz. This theoretical level is useful as an indication of the very high level of these signals relative to those from other sources. However, the actual level at such short range will be substantially different because of the extreme extrapolation involved (the closest range at which measurements were taken was 8 km). At the longest ranges studied (28.7 km), the sleeve exploder signature 'chirped' from about 200 Hz down to 100 Hz, indicating that that range of frequencies probably propagates best in shallow waters of the eastern Beaufort Sea. That is also the frequency range of many of the bowhead calls.

Drillship and dredge sounds were continuous during the periods of measurement, but not always very stable in their characteristics. The dominant tonal component in the drillship signature was at 278 Hz (evidently from the main power plants) at a predicted level of 133 dB//1 µPa at 100 m. The dominant dredge tone was at 380 Hz and its predicted level at 100 m was 120 dB//1 µPa.

Transmission loss was examined using the equations fitted to received signal levels vs. range. These equations revealed that a cylindrical spreading term (10 log R) plus an absorption loss term (linear function of R) provide a good description of received levels. The absorption loss term is frequency dependent but insufficient data prevent us from determining the exact form of the relationship. The absorption loss term for one type of signal at 80 Hz was 0.17 dB/km, and that for another type of signal at 1000 Hz was 2.53 dB/km. However, the results at middle frequencies were inconsistent.

INTRODUCTION

Marine mammals (including bowheads) use sound to communicate and to receive information about their environment. Sound travels very efficiently in water, day or night, winter or summer, and regardless of the water's clarity. At least in deep water, the intense, low-frequency sounds produced by baleen whales, including bowheads, are believed to be transmitted especially well and with little attenuation (Payne and Webb 1971). The very advantages of underwater sound that have been so useful to marine mammals give rise to potential problems related to underwater industrial sounds (Acoustical Society of America 1981). Many industrial sounds are also intense and of low frequency, and consequently are transmitted efficiently over relatively long distances. Thus, the acoustic effects of industrial operations may be manifested far from their source, and this greatly expands the area potentially affected. Possible ways in which underwater industrial sounds could affect whales include direct disturbance and the masking of important communication, echolocation and/or environmental sounds (Fraker and Richardson 1980; Møhl 1981).

Offshore Exploratory Activities in the Eastern Beaufort Sea

Our studies in 1980-81 were based at Tuktoyaktuk, Northwest Territories--the base of operations for offshore oil and gas exploration in the eastern Beaufort Sea (Fig. 1). These operations provide opportunities to record industrial sounds that might cause disturbance to bowheads. The main offshore operators are Dome Petroleum Ltd., Esso Resources Canada Ltd., and Gulf Canada Resources, Ltd.

Dome, through its subsidiary Canmar, operates four drillships and a fleet of supply and auxiliary vessels. Helicopters frequently travel from Tuktoyaktuk to the drillships. The drillships usually drill in water 20 to 100 m in depth.

Esso's offshore activities center around the construction of man-made islands which are used as platforms for exploration drilling. Most islands have been built during the open-water period, although some were built during winter. Initially the islands were built in shallow (1-9 m) water, but

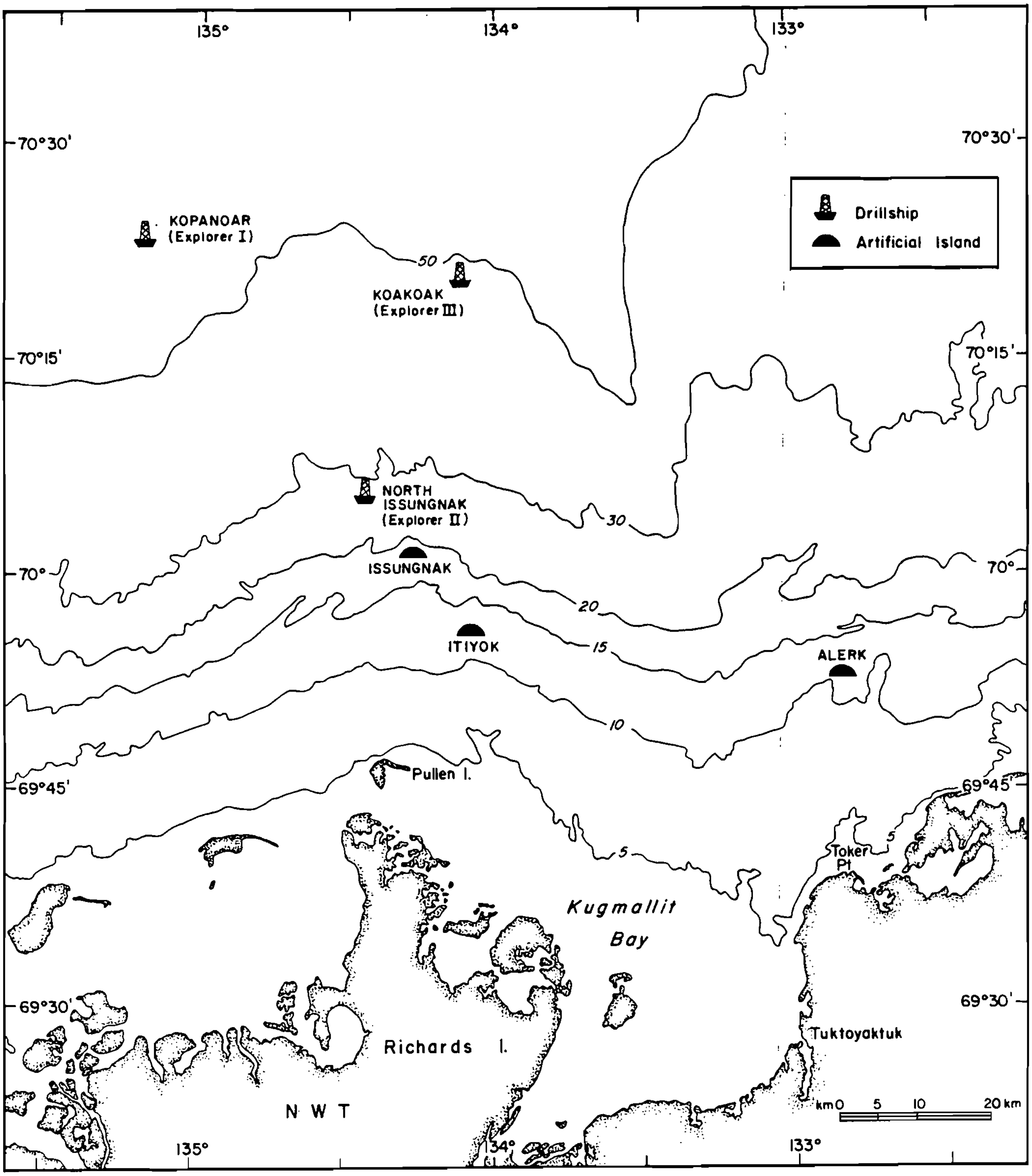

FIGURE 1. The region off Tuktoyaktuk, N.W.T., where most recordings of industrial sounds were obtained. Drillship locations in August 1981 are shown. Water depths are in metres.

during 1977-81 islands were constructed in water 13-19 m deep. Most of the material for the latter islands was dredged from around the island sites by the suction dredge 'Beaver Mackenzie'. In 1980, an island at Issungnak (19 m depth) was completed and another at Alerk (13 m depth) was begun. The latter was completed in 1981 and another (Itiyok) was begun. In addition to the dredge, island-building operations involve tugs, crew boats, barges, and a barge camp.

In addition to drilling operations, ship-based underwater seismic exploration takes place in the eastern Beaufort Sea during the open water season. Dome and Gulf use an 'airgun' array; each airgun releases a charge of compressed air as the energy source. Esso uses a 'sleeve exploder', which is a very strong rubber cylinder into which a charge of propane and oxygen is injected and ignited by an electric spark. The rapid combustion produces the required energy pulse, and the exhaust gases are vented to the surface through a hose. Seismic exploration produces very strong waterborne noise (see below).

Review of Previously Existing Knowledge

Industrial sounds can be intense, and often much of their energy is in the low frequency range. This range overlaps the main frequencies of baleen whale sounds. Thus there is a potential for industrial sounds to mask the communication or other sounds of whales (Payne and Webb 1971; Myrberg 1978). In deep water, low frequency sounds often propagate over long distances, especially in the arctic. Thus the area affected by industrial sounds could be large.

The distance at which a sound may be detected depends on characteristics of the source, the transmission path, and the receiver. More specifically, detection range depends

1. on the source level, frequency, bandwidth, directional characteristics and depth of the sound source,
2. on transmission losses between the source and the potential receiver,
3. on the sensitivity, directional characteristics, and lowest acceptable signal-to-noise ratio of the receiver, and

4. on the level and characteristics of ambient noise at the receiver.

The potential effects of these factors on detectability of low-frequency sounds produced by baleen whales have been reviewed by Payne and Webb (1971). They show that the very intense sounds produced by many baleen whales (Thompson et al. 1979) are, in some deep-water areas, potentially detectable for hundreds of kilometres even if rather conservative assumptions are made. However, noise levels, water depth and transmission properties of the ocean strongly influence these estimated distances.

This section is organized into three parts concerning (1) relevant ambient noises, (2) sound propagation phenomena, and (3) industrial noises.

Ambient Noise

Ambient noise in arctic waters has been studied extensively (Macpherson 1962; Milne and Ganton 1964; Greene and Buck 1964; Payne 1964; Ganton and Milne 1965; Milne 1966; Milne et al. 1967; Greene and Buck 1979; Diachok 1980; Buck 1981; Greene 1981; Leggat et al. 1981). The noise of the Beaufort Sea has been found to have both seasonal and regional dependencies.

During **summer**, studies in other waters indicate that wind-dependent sea noises and biological noises will predominate. In open water regions where there is little shipping or industrial noise, noise spectra are relatively flat from 20 to 500 Hz, and decrease above this frequency at about 5 dB per octave (Ross 1976). Increased wind speed and sea state result in increased noise levels across the spectral range. Shipping noise, where it is intense, is a major component of low-frequency ambient noise, with peak energy below 100 Hz (Wenz 1962; Ross 1976).

Ambient noise levels in shallow open water are highly variable (Myrberg 1978). Data from a drifting buoy in the Chukchi Sea indicated that average sound levels were lower in shallow than in deeper water (Buck 1981).

Noise levels near the edges of fields of pack ice are generally quite high. Noise levels decrease with increasing distance from the ice edge, but decrease more rapidly with distance under the ice than with distance out into the open water (Diachok 1980).

During **winter**, the ice-covered sea consists of three main regions with different noise characteristics. One is the so-called shore-fast ice found in shallow waters and effectively locked to the land and offshore islands. The second is the polar pack ice drifting under the influence of wind and current. The zone between the two is called the shear or transition zone.

The noise beneath solid shore-fast ice is primarily the result of thermal cracking and wind blowing over the surface. Generally the levels are lower than are expected in the polar pack ice. Noise in the pack is dominated by ice deformation--the grinding of floes together under the force of wind--even though there may be no wind at the site of active ice. Thermal noise is far less important. Wind noise over the ice is more important at higher frequencies (1 kHz and above).

Measurements of the source level of an active pressure ridge have been made (Buck and Greene 1979; Greene 1981). Tonal components were observed to come and go over periods of several minutes at frequencies as high as 200 Hz. Source levels of these tones were variable but reached levels as high as 136 dB re 1 μPa (referred to one metre). These results may be important in assessing what levels and types of noises bowhead whales are exposed to in the absence of oil- and gas-related activities. Bowheads overwinter in the pack ice of the Bering Sea, and the spring migration of bowheads takes them through the pack ice during late April or early May when pressure ridges are still forming (Braham et al. 1980a,b).

The pack ice noise levels in the deep water of the Beaufort Sea have been measured over a period exceeding one year, providing statistics on the noise for each season (Greene and Buck 1979; Buck 1981). Frequencies below 1000 Hz were studied. The months of January - March were found to be the noisiest, with declining noise from April to June, and lowest noise levels during the summer months of July to September.

Underwater Sound Propagation

Numerous factors influence the propagation characteristics of underwater sounds. Some of these are channeling, absorption and scattering (all of which are frequency dependent), as well as spreading. The presence and characteristics of ice also affect the propagation of waterborne sound. The frequency of the sound waves affects their behavior when they intersect an interface (water surface, underice surface, seafloor). High frequencies are absorbed significantly by the bottom and scattered by the roughness of the underice or water surface. Low frequencies are not as significantly absorbed or scattered.

Two basic types of spreading are normally considered: spherical and cylindrical. Spherical spreading occurs when sound spreads in three dimensions from the source (i.e., over the surface of an expanding sphere). In this case, signal strength decreases 20 dB for each 10-fold increase in range. Cylindrical spreading occurs when sound spreads in only two dimensions (i.e., over the surface of an expanding cylinder of small height relative to its radius). In this case, signal strength decreases 10 dB for each 10-fold increase in range. In general, spreading from a point source is assumed to be more or less spherical near the source and cylindrical beyond some transition distance. Thus a sound may, due to spherical spreading, be 40 dB less intense 100 m from the source than at 1 m from the source. However, due to cylindrical spreading it may diminish by only another 30 dB between 100 m and 100 km if absorption and other losses are minimal.

In the arctic, sound is often channeled into the near surface zone. When channeling occurs, spreading is approximately cylindrical and sound rays propagating obliquely downward are often refracted back toward the surface because of pressure and temperature effects. In particular, this occurs when surface temperatures are lower than temperatures in deeper water. When low frequency sound waves, refracted or reflected, encounter the underice or water surface, they are reflected downward at the same angle, whereupon the refraction/reflection cycle repeats. These two processes acting together tend to cause propagating sound energy to remain in the near-surface zone, and to a first approximation this results in cylindrical rather than spherical spreading.

Just as is true for the ambient noise, sound propagation in the Beaufort Sea varies markedly with season. In **winter,** when there is essentially solid ice cover, the lowest temperature is at the surface. This creates a positive sound-speed profile (higher speeds at greater depths) and a resultant upward refraction of sound rays. This situation is characterized as a so-called 'half sound channel' with its axis at the surface. Considering sound ray propagation, an acoustic source at the surface would be expected to insonify the medium best. However, the effect of the pressure release boundary makes the surface the least desirable location for a source of acoustic energy. Increasing the source depth improves the coupling, with high frequencies benefiting first. At source depths of 20 m or more, all frequencies >10 Hz propagate well.

In **summer** the sound speed structure changes in those areas without ice. The surface heats up, and the action of waves mixes the upper regions to form a warmer isovelocity layer on top. Depending on the depth and the extent of mixing, the bottom water may remain near 0°C. Thus, in shallow coastal waters the sound-speed profile may show a sharp negative gradient or it may be isovelocity to the bottom. Generally, the two-layer, negative gradient case may be expected and sound rays will be refracted downward. Bottom material and structure will strongly influence the sound propagation, with sediments resulting in marked absorption. However, at low frequencies the sound may travel well in the bottom, refracting upward and reentering the water column at considerable distances from the source. As a result, acoustic energy at low frequencies may travel through the bottom while energy at high frequencies travels through the water.

Near shore, rivers may contribute fresh water to ocean areas. The temperature and salinity will differ from the sea water in such a way that anomalous sound propagation conditions may result.

Sounds from Industrial Sources

Virtually every activity involving the operation of machinery in and near the ocean has the potential for generating underwater sound. In this section, six such activities are considered. The noise from seismic surveys is also discussed.

Ship Noise --Ships and boats operating in the Beaufort Sea may vary from small launches to large transport vessels and icebreakers. If some of the present plans proceed, much larger icebreakers and supertankers may soon be present in the Beaufort Sea. While underway, propeller blade noises may be expected to dominate at low frequencies. For shallow-draft, fast boats, as in the case of a high-speed water taxi or launch, blade sounds may couple well at moderate frequencies. Large vessels with deep propellers may radiate substantial levels of sound pressure at low frequencies (Cybulski 1977). Propulsion and auxiliary machinery on ships also generates noise. Such noise is distinctive from blade and shaft noise in that it is generally higher in frequency and lower in level.

Ford (1977) reported source levels of 150-165 dB re 1 μPa (referred to 1 m) for tugs and crew boats in the eastern Beaufort. Cummings et al. (1981) report on noises from tug boats operating in Prudhoe Bay in the West Dock area. The water depth was 2.4 m and the hydrophone depth was 1.2 m. A 200 kW diesel driven generator was operating in a large, floating wooden barge nearby. For the tug operating 110 m from their hydrophone, they found that 'Nearly all of the lower-level tonals of the generating plant [were] obscured by the powerful broadband sound of the tug...'. The overall received level 110 m from the tug was about 115 dB. They report finding no salient tonal components and attribute that to masking by broadband noise.

Noise from larger vessels has not previously been measured in the Beaufort Sea. Data from other areas indicate that, to a first approximation, sound levels tend to increase with ship speed and size (Ross 1976). There is no direct information about the source levels of large icebreaking tankers (which have not yet been built). However, formulae relating noise levels of smaller ships to ship size and speed suggest that the source level would be extremely high--in the order of 200 dB re 1 μPa (referred to 1 m). This level is some 20 dB higher than that of the fin whale calls which Payne and Webb (1971) calculate could be detectable for hundreds of kilometres in some circumstances in deep water. Leggat et al. (1981) assess the noise levels likely to be produced by large icebreaking LNG ships.

Icebreakers --In addition to ship noise, icebreakers contribute the sounds of breaking ice. The sound of ships breaking ice has recently been recorded, but few analyses are available. In the pack the ice breaks against itself naturally. However, ice deformation from natural causes is a much slower process than occurs when an icebreaker forges ahead, and at least the rate of deformation, if not the noise level, is much greater. In areas of shore-fast ice, pressure ice activity is uncommon and the noise made by icebreakers might be unfamiliar to marine mammals there. In both the pack ice and shore-fast ice regions, the propulsion-related sounds of an icebreaker may be expected to vary as the ship stops, backs and rams ahead (Thiele 1981).

Aircraft Noise -- The theory of the underwater reception of airborne sound has been reported by Hudimac (1957), Weinstein and Henney (1965), Young (1973), Medwin and Helbig (1972), Urick (1972) and Waters (1972). Urick reports measurements of sound from a prop jet over deep water, while Medwin and Helbig report measurements of helicopter sound. In shallow water with good transmission conditions the waterborne sound from a passing aircraft may persist detectably much longer than the airborne sound. Sounds from aircraft flying near sonobuoys are often received perceptibly at the sonobuoy hydrophones (Ljungblad and Thompson 1979; this study). In deep water the most important path for sound energy is the direct refracted path, and Urick reports 'the source in air may be replaced by an equivalent inwater source having a cosine squared directivity pattern and a source level 7 dB less than that of the real source'.

Drilling Noise -- Waterborne drilling noise may come from drillships, semi-submersibles, platforms, or islands (natural or artificial). Different activities associated with drilling may generate different types of noises, and noises may originate on the platform or from the drill string. Recently, efforts have been made to measure the levels and frequency characteristics of drilling noise in the water.

In the Prudhoe Bay area, measurements were made in March 1979 of noises from drilling rigs on two islands, one natural and one artificial (Malme and Mlawski 1979). Their recordings were made in shallow water beneath the landfast ice that surrounded the islands. Most of the energy was below 200 Hz, with tonal components predominating below 100 Hz. The broadband noise level was highest when the rotary table was turning, an effect attributed to 'loud impact sounds which occurred at a once per revolution rate'. The 'diesel engines and other rotating machinery' produced the tonal components. The investigators observed the low frequency tones to ranges of 6.4-9.6 km under low ambient noise conditions and to about 1.6 km under high noise conditions. Specific frequencies reported were 5, 12, 21, 23, 29 and 80 Hz. They estimated that 'for spring and summer open water conditions a five Hz tonal component ... may be detectable out to about five miles [8.0 km] seaward from the rig'. Water depths for these data were 2-12 m, and ice thickness was about 1.5 m. It is unknown how noise from drilling on an artificial island in open water may compare with the above results from icebound islands.

A review of the literature on underwater noise from offshore oil operations (Turl 1980) reported other measurements of noise from drilling operations. Sound levels from a semi-submersible platform (SEDCO J) in the north Atlantic were reported by Buerkle (1975). His recordings were made over a 1.5 h period of slack tide and included tripping (retrieval and replacement of the drill string), drilling, and sounds from the 56 m guard boat. The water depth was 63 m and the range to the hydrophone was 583 m. Analysis of all three types of sounds showed a spectral peak in the one-third octave band centered at 16 Hz. The levels at 16 Hz, assuming spherical spreading, were 127 dB//1 μPa at 100 m for drilling, 123 dB for tripping and 129 dB for the guard boat. High spectrum levels, which do not appear to be from tonals, appear for tripping in the 160 and 200 Hz bands; the levels are near 127 dB//(1 μPa)^2/Hz at 100 m. Schmidt (1980) recorded drilling sounds from a semi-submersible in Cook Inlet, southern Alaska. Peak recorded energies occurred near 80 Hz, but there may have been another spectral peak at very low frequencies (below 16 Hz). More detailed results from several semi-submersibles will be forthcoming in a report by R.S. Gales (in prep.).

Noise of a drillship and associated vessel operating offshore in the eastern Beaufort Sea was recorded in 1980 and 1981 (this study).

Production Platforms -- Measurements of noise from platforms have been reported for rigs in Cook Inlet (Schmidt 1980). However, the preliminary analyses were not performed in a manner paralleling the previously reported work and quantitative comparisons are not feasible at this time. In general, peak noise levels were apparently at low frequencies (below 100 Hz). More details will be forthcoming in a report by R.S. Gales (in prep.).

Dredging Noise -- Measurements of dredging noise have been reported for two sites in the Beaufort Sea (Ford 1977; see also Turl 1980). However, no data were reported for frequencies below 250 Hz. Most of the recorded sounds were composite noises from various combinations of tugs and crew boats as well as the dredge. Most energy was apparently in the 250-1000 Hz frequency range, with the peak usually below 1000 Hz. Propagation characteristics of these sounds were examined; in general, the sounds were attenuated rapidly in the shallow nearshore waters. Recordings of dredging were made at artificial islands in somewhat deeper water in the eastern Beaufort Sea during the summers of 1980 and 1981 (this study).

Seismic Survey Noise -- Impulsive signals with very high peak amplitudes are used in underwater seismic survey work. Explosives, spark discharges, sleeve exploders, and airguns can be used to generate the signal (Kramer et al. 1968; Fricke et al. 1981; Johnston and Cain 1981). The last two methods are commonly employed in the Beaufort Sea. We have seen no reports on sound level measurements in the Beaufort Sea, although Ljungblad et al. (1980) mention that seismic surveys in the Alaskan Beaufort employ techniques with a source level of 248 dB (± 10 dB) re 1 μPa at 1 m. Seismic signals were recorded and analyzed in this study.

Other Noises -- Cummings et al. (1981) had occasion to record the sounds from gravel pit explosions at Prudhoe Bay. Typically, gravel is loosened from its bed by a closely phased series of explosions designed to leave a large pile for easy loading. An explosion once per day provides sufficient gravel for the various road and artificial island construction projects that may be underway. Three or more gravel pits may be in operation at one time in the Prudhoe area. At a range of 14.7 km, 11 km of which were across the bay, in water only 1.5 m deep, sound from an explosion was detected in the frequency band from 2 to 18 kHz. The highest levels were between 5.5 and 9.5 kHz. The propagation path of ground and shallow water may not have supported transmission of sound at low frequencies. The data were recorded on 23 September, 1980, just when the bay was freezing over to the point of becoming unnavigable. On the following day, they recorded the sound from a similar explosion, but under different circumstances. The range was 9 km but the hydrophone was immersed on the bottom of the North Slope Borough's man-made reservoir. A 3 m pipe provided access to the water, which was 3.7 m deep.

In this case, there was considerable energy in the 0-1 kHz band with a preponderance below 500 Hz.

Snow machines are widely used by Alaska Eskimos traveling across shorefast ice. Holliday et al. (1980) reported on the sounds of snow machines recorded in May and June and observed that '...levels may be more directly related to the condition of the surface than the speed of the vehicle'. Evidently, the softer snow surface in June resulted in transmission of less noise into the water.

Cummings et al. (1981) recorded sounds from an artificial island in the Prudhoe Bay area on 14 September 1980, before freezeup. Gravel bags were being filled and placed on the periphery of the island for erosion protection. At 457 m, the overall level in the band from 0 to 10 kHz was 84 dB. The banging sounds from a crane increased the levels in the band from 1,500 to 10,000 Hz by about 13 dB.

Approach

Industrial and ambient sounds were recorded and analyzed for two main purposes:

1. It was important to know the characteristics of the waterborne sound at locations where bowhead behavior was observed. Information about ambient and industrial sounds was needed to interpret the behavior of the animals near full scale industrial operations, and also on occasions when we conducted experiments to simulate industrial operations (see 'Disturbance' section, Fraker et al. 1982).
2. Characteristics and propagation of industrial sounds in the Beaufort Sea are, in general, poorly known (see above). Without such knowledge it is difficult to predict the potential nature and radius of noise effects on bowheads.

In addition, sounds produced by the bowheads themselves were an important part of the study. Our efforts to record waterborne sounds near bowheads provided data on ambient, industrial and bowhead sounds. The bowhead sounds are described in the 'Normal Behavior' section (Würsig et al. 1982).

A Sony TC-D5M cassette tape recorder (with a servo capstan drive for speed stability) was used to record the hydrophone signals. An adjustable gain amplifier (40 to 80 dB) provided amplification of the hydrophone signals before tape recording. One tape recorder channel was used for the data, the other for voice announcements.

Airborne System

The airborne system was based on the use of AN/SSQ-41B and AN/SSQ-57A sonobuoys deployed from a Britten-Norman Islander aircraft used for observing bowheads. Aircraft position at the time the sonobuoys were dropped was determined from the onboard VLF/Omega system and the aircraft's radar. The normal hydrophone depth was 18 m or the bottom, whichever was less. Attempts to modify the sonobuoys to reduce hydrophone depth to 9 m in 1981 generally failed.

The -57A sonobuoys came with calibration information. The -41B sonobuoys are functionally the same, but rather than being individually calibrated they are specified to have a sensitivity falling within the envelope in Fig. 2. The average of the calibration points (at each frequency) for the 20 -57A sonobuoys received for project use fell close to the center of the envelope in Fig. 2, so those averages were used for the sensitivity values of the -41B sonobuoys.

In the aircraft, a Nems-Clarke wideband telemetry receiver (model R1302-B) was used in 1980 to receive and demodulate the FM signals from the sonobuoys. In 1981 two frequency converters were built for use with two high quality portable FM receivers (Sony ICF-2001) to permit reception and recording of two sonobuoy signals simultaneously. The audio output was taken from the receivers at the discriminator output and amplified externally to assure good response down to 10 Hz. A Sony TC-D5M cassette recorder was used to record the audio signals. An observer on the aircraft provided voice announcements.

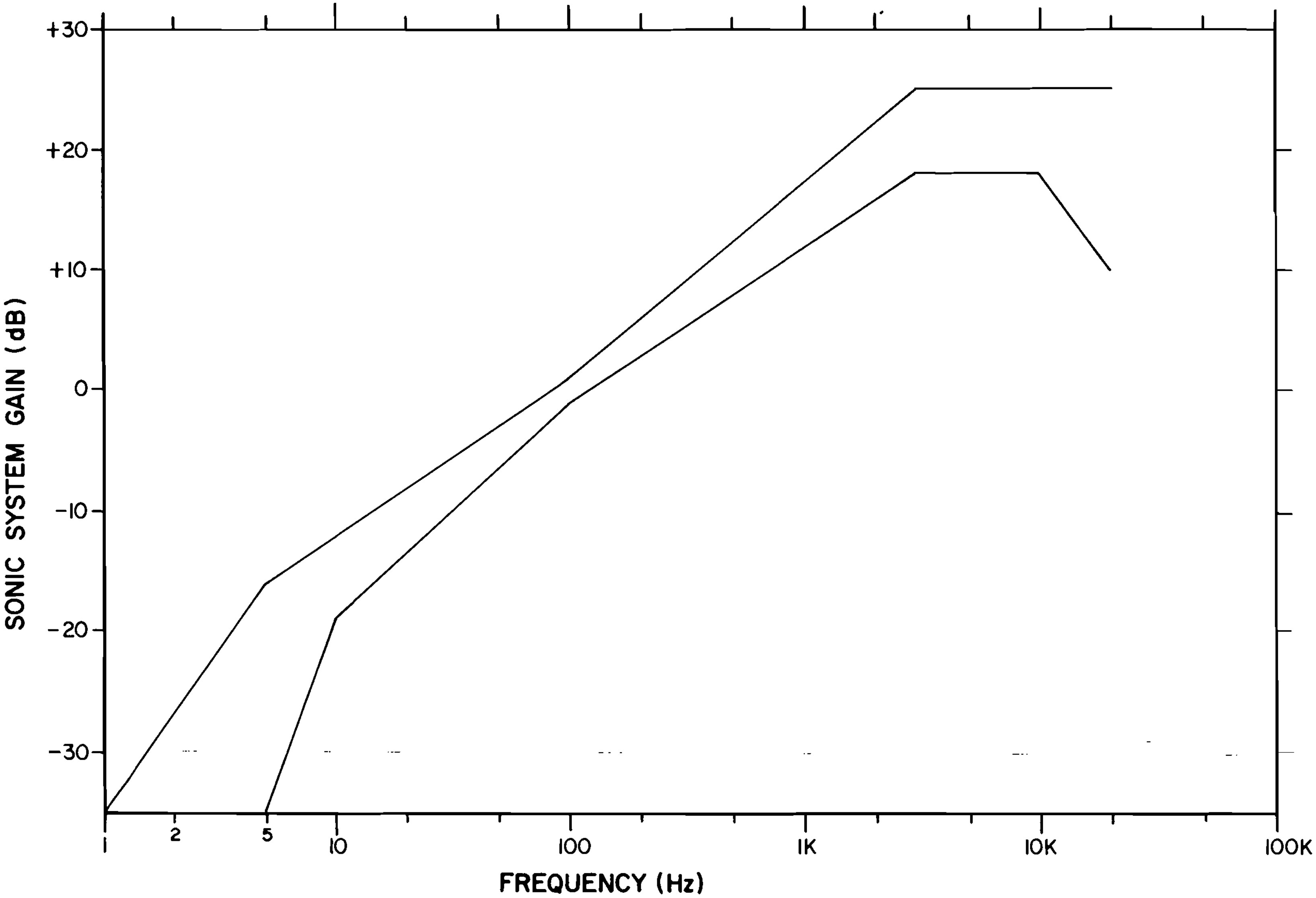

FIGURE 2. Frequency response envelope for AN/SSQ-41B sonobuoys (from Military Specification, sonobuoy AN/SSQ-41B. MIL-S-22793E (AS). U.S. Navy, 24 p., 1979). The response for the AN/SSQ-57A sonobuoys used in 1981 fell within the envelope shown here.

Methods of Acoustic Data Analysis

The analysis of acoustic data was basically the same for both the boat and the aircraft data. The objective was to determine the received signal spectrum levels for various recording sections, and the approach was to use a general purpose minicomputer with an analog-to-digital converter to convert the analog signals on the tape to 12-bit samples for power spectrum analysis. The computer applied various calibration constants and generated plots of the computed spectra. Calibration data that were taken into account included the sensitivity-frequency curves for the hydrophone, sonobuoys and receivers, and the gain characteristics of the tape recorders.

The signal analysis methods used for the various noises recorded did not vary substantially except in two respects:

1. Sometimes spectrum levels in the 10-500 Hz band were averaged over 4 s and at other times over 16 s. A 16 s averaging time was standard, but a 4 s period was sometimes used in cases of rapidly-varying signals, such as aircraft flyovers.
2. Levels and frequencies of impulsive seismic survey signals were analyzed with respect to time, since they changed rapidly. No power spectra were computed for seismic survey signals.

With these two exceptions, analysis techniques were standardized as described below.

Averaged Spectra

Five sample rates were used in the analysis of each tape segment selected. These provided a range of frequencies and spectral resolutions as shown in Table 2. The Blackman-Harris minimum 3-term window (Harris 1978) was applied to each segment of data before the discrete Fourier transform was computed for that segment, thereby suppressing 'leakage' from tonal components not falling in the exact center of an analysis bin. The window resulted in the effective width of each analysis bin being 1.71 times the bin spacing.

Table 2. Parameters of power spectrum analysis

Sample Frequency	Bin Spacing	Effective Bin Width	Filter Cutoff*	Length of Record Analyzed
1024 Hz	2 Hz	3.4 Hz	500 Hz	16 s
2048	4	6.8	1000	8
4096	8	13.7	2000	4
8192	16	27.4	4000	2
16384	32	54.7	8000	1

*The lowpass filter cutoff is also the upper limit of the frequency axis on the resulting graph.

Regardless of sample rate, 16,384 samples were stored and processed, and the discrete Fourier transform was routinely computed for 512 samples. This assured identical statistical stability in analyses, but it meant that different lengths of recording were analyzed, depending on the sample rate. The length of recording analyzed ranged from one second at the highest rate (16,384 samples/s) to 16 s at the lowest rate (1024 samples/s). This would be unimportant except that the received signals were not steady and fluctuated with time, either as a result of motion of the source or because of variations in the activities producing the sounds.

Because some events are of short duration (like aircraft flyovers at low altitudes), a special analysis was sometimes used for the 10-500 Hz band. Samples were taken at 4096 samples/s but analyzed in blocks of 2048 rather than 512. This meant that 4 s data were averaged rather than 16, but the bin spacing remained 2 Hz.

In all spectrum analyses the segments analyzed were overlapped by 50%. This served to overcome the loss in data utilization which would have resulted if the 'window' had been applied to consecutive segments.

Spectrograms

To show the temporal variability of certain sounds, 'waterfall'-type diagrams were produced by computing the power spectrum for frequencies up to 1000 Hz for many successive portions of a brief record. For comparison, some is both awkward and confusing. 'Spectrum density' and 'power spectrum density' or 'power spectrum' are other terms used to describe the levels of broadband signals and noises. Note: 'spectrum level' is not the mean square pressure in a one hertz band unless the signal spectrum is constant in that band. Generally, a sound is analyzed with some non-zero bandwidth filter and the result is 'reduced to a 1 Hz band' assuming implicitly that the spectrum is constant across the analysis band.

Broadband Level: The total mean square pressure level of a signal in a wide frequency band. 'Wide' generally means large compared to 1 Hz. The broadband level is obtained by integrating spectrum levels over the band. Narrowband components (tonals) falling within the band should be included.

Spherical Spreading: The attenuation of intensity or power proportional to the square of the distance traveled. It is described in dB by 20 log (R2/R1) where R1 is the reference range. Ideally, spherical spreading is ascribed to sound propagation where the surface and bottom are far removed from the source and receiver, and the ray paths are not refracted significantly. With spherical spreading the attenuation rate is 6 dB per distance doubled.

Cylindrical Spreading: The attenuation of intensity or power proportional to the distance traveled. It is described in dB by 10 log (R2/R1) where R1 is the reference range. Ideally, cylindrical spreading is ascribed to sound propagation where the source and receiver are far apart compared to the water depth. The surface and bottom reflections or special channeling processes serve to retain the energy within the water. With cylindrical spreading the attenuation rate is 3 dB per distance doubled.

Doppler Shift: An apparent change in frequency of a signal resulting from relative motion of the source and receiver along a line between the two. For a source of frequency F_s moving toward a receiver at speed V in water with sound speed C, the frequency at the receiver F_r is given by $F_r = F_s/(1 - V/C)$.

Units of Pressure : $1 \text{ Pascal} = 1 \text{ newton/m}^2$
$1\ \mu\text{bar} = 1 \text{ dyne/cm}^2$
$1 \text{ Pascal} = 10\ \mu\text{bars}.$
$100{,}000\ \mu\text{Pa} = 1\ \mu\text{bar}.$

Thus, sound level (dB//1 μPa) = sound level (dB//1 μbar) + 100.

RESULTS

Sound Speed Structure of the Eastern Beaufort Sea

Knowledge of the sound speed structure in an area is important when sound transmission loss is of interest or, as in our study, when sounds are to be measured at different distances from the source. As part of the bowhead 'Feeding Areas' study in 1980 (Griffiths and Buchanan 1982), temperature and conductivity profiles were taken on three occasions at three locations. The profile extending to the greatest depth was selected at each of the three locations, and corresponding sound speed profiles were computed using an equation in Urick (1975). Then, representative sound ray paths were computed for each sound speed profile. In each case the assumed source depth was 5 m and the initial ray angles were -8, -5, -2, and +1 degrees from the horizontal. The results are shown in Figure 3.

The first profile data came from 'Ungaluk' on 14 August near Issungnak Island (Fig. 3A). There is a small channel with its axis at 5 m depth, but the dominant feature is the negative gradient of sound speed in the bottom half of the water column. The King Point profile on 20 August indicates the presence of a small surface channel (upward refraction, surface reflection), but a dominant negative gradient below 5 m (Fig. 3B). The profile taken from the 'Imperial Sarpik' on 26 August (Fig. 3C) was taken near the location of the 'Ungaluk' profile, and it is interesting to note the effect of the warmer surface water present on 26 August. The major feature is again the strong negative gradient below 7 m. These negative gradients cause sound rays to be refracted downward, assuring many bottom reflections. In this case, as in other shallow water areas, the type of bottom will, because of its absorptive and dissipative properties, have a strong influence on sound propagation.

In 1981 all the temperature-conductivity profiles were taken in the areas of oil industry activity north and northwest of Tuktoyaktuk. Three representative profiles taken at places and times close to those where noise measurements were obtained have been converted to sound speed profiles in the same manner used for the 1980 profiles (Fig. 4). The general conditions were

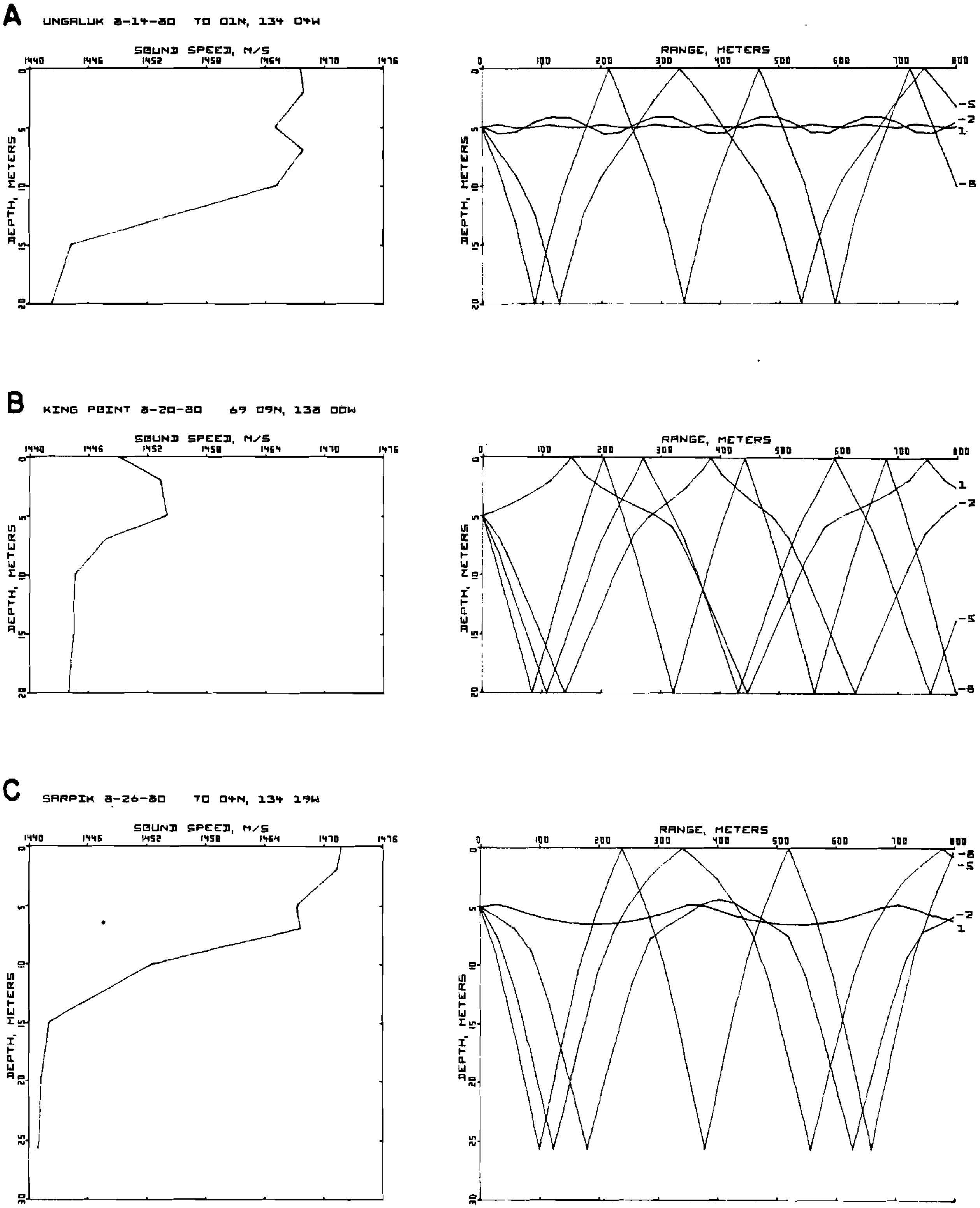

FIGURE 3. Computed sound speed profiles and ray paths for three locations in shallow waters of the eastern Beaufort Sea during August 1980.

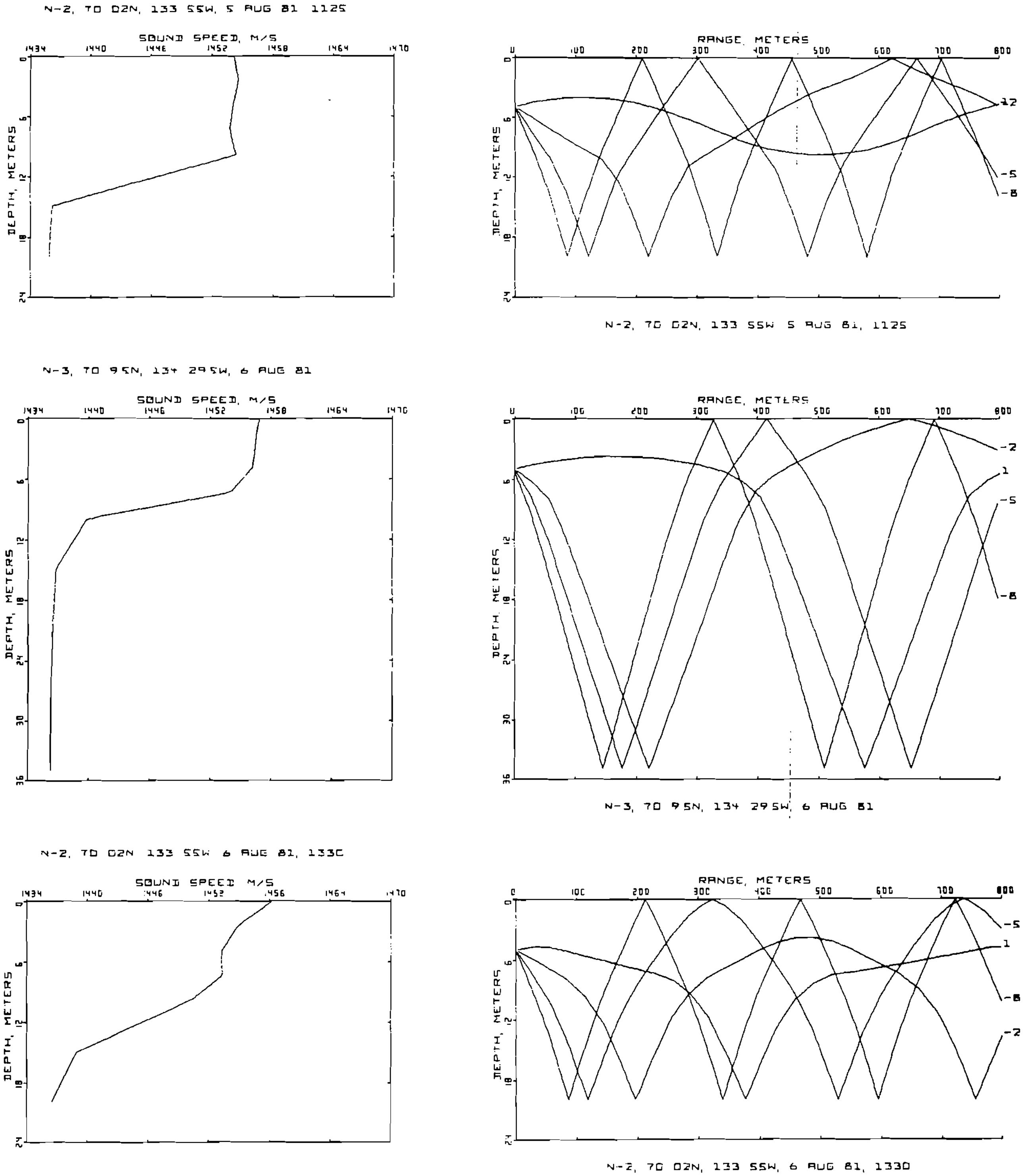

FIGURE 4. Computed sound speed profiles and ray paths on three occasions in the shallow waters of the eastern Beaufort Sea during August 1981.

the same in 1981 as in 1980; 'high-speed' water extends to 8 or 10 m, below which the sound speed drops sharply. Below about 15 m the speed is close to constant. The effect on sound propagation is downward refraction of sound rays and a resulting series of reflections between bottom and surface.

Sharp impulses of sound, such as originate from air guns, sleeve exploders, and other seismic survey sources, contain a broad spectrum of energy. As these impulses travel by a series of reflections between surface and bottom, the interference effects serve to emphasize specific frequencies depending on the number of bounces and the range. For a given range, high frequencies are emphasized first, then low frequencies, and the signal that began as an impulse appears as a chirp-like burst of energy. At longer ranges the chirp is longer. The upper frequency is limited by the absorption losses in the water and the bottom as well as scattering losses with surface reflections. The lower frequency is limited by the ducting effect of the shallow water. The band of frequencies present in the sleeve exploder signals after travelling on the order of 25 km extends from about 100 to 200 Hz.

Ambient Noise

It is important to establish a baseline of noise levels against which to compare the levels of noise received from industrial sources. It is also useful to compare the background levels in the present study area with those observed elsewhere. However, it was impractical to collect an unbiased representation of ambient noise samples using our techniques, which were designed for other purposes. Those techniques were suitable for acquiring samples of whale noises and industrial noises, but both the boats and the Islander aircraft operated only in fair weather. Thus, noise samples from stormy weather conditions, when higher noise levels would be expected, were not obtained. Special instrumentation designed to collect underwater acoustic noise samples systematically without human involvement would be required in a detailed study of ambient noise.

Three sections of a sonobuoy recording made on 29 August 1980 were selected for analysis as being representative of times of low background noise. The recording was made because bowheads were in the area, but the sections analyzed were not believed to contain bowhead sounds. Evidently there is some weak contamination from aircraft sounds (the recording aircraft). The sonobuoy was dropped at 70°49'N, 129°06'W, at about 13:18 MDT. The water depth as determined from hydrographic charts was 24.5 m, and the hydrophone was suspended at 18 m.

The received spectrum levels in Figure 5A are presented as being representative of ambient noise at low frequencies. The 60 Hz tone may have come from the sonobuoy receiver, which was ac-powered from inverters on the aircraft. The source of the other tones is probably the aircraft. No tones were detected above 250 Hz (Fig. 5A). The levels are not high, generally being below 70 dB. Urick (1975) reports the average level of World War II measurements in bays and harbors (shallow water) as being 80 dB at 100 Hz and 64 dB at 1000 Hz; distant shipping noises in deep water result in levels between about 58 and 79 dB at 100 Hz. By comparison, our sample seems relatively quiet; the non-tonal (broadband) level at 100 Hz is about 52 dB.

The received spectrum levels at higher frequencies may be seen in Figure 5B, which extends to 8000 Hz. Note that the levels above 7000 Hz trail off artificially because of the lowpass filter set at 8000 Hz to prevent aliasing errors. Levels at four frequencies from this figure and from two other sections of the same recording, along with a deep water average for zero wind, are presented below:

	Recorder Turns				
Frequency, Hz	015	062	660	Deep Water, Beaufort Force 0*	Deep Water, Beaufort Sea Summer Median**
1000	39.6	41.8	40.0	43.	38.5
2000	35.0	35.7	35.7	38.	
4000	30.7	30.8	30.8	33.	
8000	27.0	25.0	24.0	28.	

* From Urick (1975).
** From Polar Research Laboratory, Inc. (unpubl. data).

The values in the '660' column are those from Figure 5B. The levels at 8000 Hz were adjusted to compensate for the filter rolloff. Note that the change

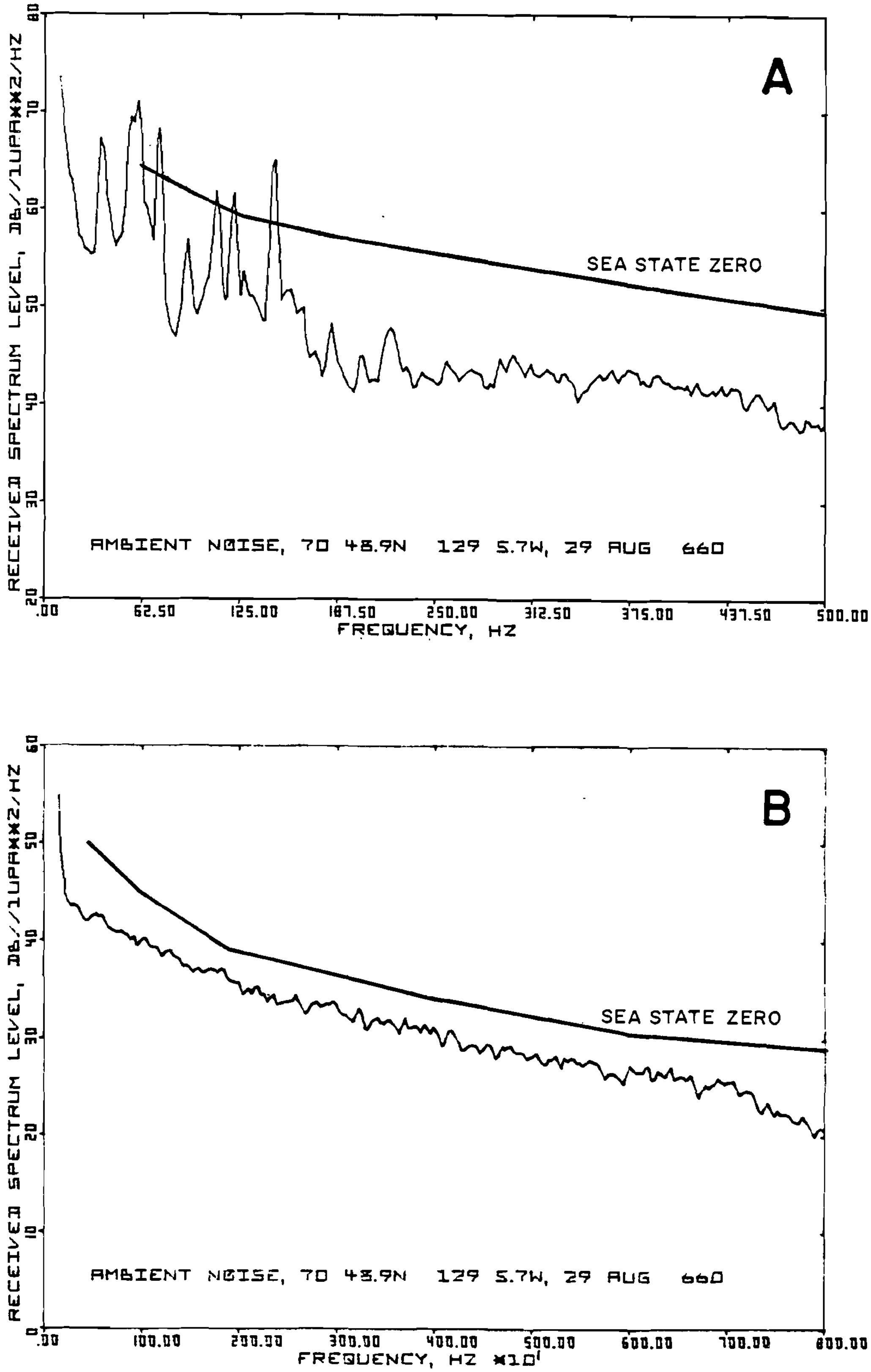

FIGURE 5. Received spectrum levels of ambient noise in an area off the Tuktoyaktuk Peninsula, 29 August 1980. **(A)** is for low frequencies (10-500 Hz). **(B)** is for a broad range of frequencies (160-8000 Hz).

in level with frequency closely approximates the -5 dB/octave slope commonly attributed to sea noise in this range of frequencies.

Eight sections of recordings made from 'Sequel' during August 1981 have been analyzed for their background content. No spectra were below Knudsen's sea state zero (extended) levels (Ross 1976), and the presence of machinery sounds was the rule. The concept of ambient noise means different things to different people and many would be unhappy to have such machinery sounds included in 'ambient noise'. However, such sounds constituted a dominant portion of the background noise recorded in our study area.

Results of the analysis of three of the eight 1981 sections are presented in Fig. 6. 'A' and 'B' are from a recording taken in 13:51 MDT on 5 August. 'Sequel' was anchored at 70°02'N, 133°56'W in 25 m of water. The sea state was about 1.5 and the wind was 5-7 knots from the southwest. The sky was clear and the visibility was unlimited. The ship 'Arctic Surveyor' had just passed our stern at 3.5 km. At this anchorage 'Sequel' was 15 km from Issungnak Island and 20 km from the drillship 'Explorer II'. No drilling was then underway at Issungnak, but personnel and equipment were present.

'C' and 'D' in Fig. 6 are from a recording taken at 15:25 MDT the same day. 'Sequel' was in the same spot, the seismic ship 'Arctic Surveyor' had moved to 8 km and begun to shoot (meaning she had slowed essentially to a stop), and another vessel, the hopper dredge 'Geopotes X', was approaching at a range of 10.2 km. The section of recording represented in Fig. 6C,D does not contain any seismic survey noise.

'E' and 'F' in Fig. 6 are from a recording taken at 18:45 MDT on 14 August 1981. 'Sequel' was drifting in fog at 70°03'N, 134°31'W, the water depth was 20 m, and the wind was <10 knots. Machinery noise predominated. Vessels appeared on radar at 2.8 and 6.9 km, drillship 'Explorer II' was 6.5 km distant, and Issungnak Island was 7.4 km away.

Comparison of the 1980 results from an area distant from industrial activity (Fig. 5) with the 1981 results from an area with much activity (Fig. 6) reveals considerably higher levels of ambient noise in the latter

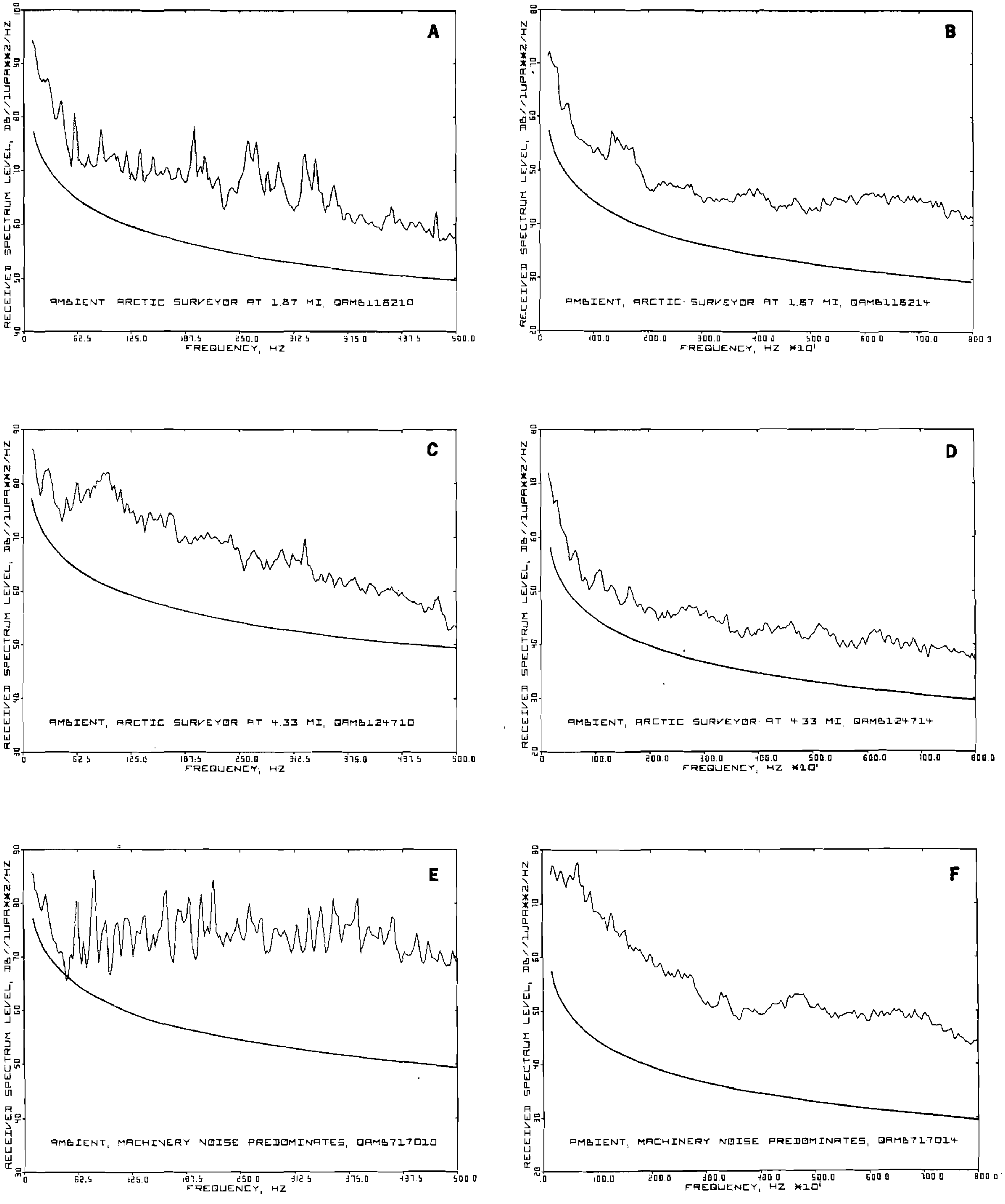

FIGURE 6. Received spectrum levels of background noise recorded from 'Sequel' on three occasions in August 1981. **(A)**, **(C)**, and **(E)** are for low frequencies (10-500 Hz). **(B)**, **(D)**, and **(F)** are for a broad range of frequencies (160-8000 Hz). The smooth lines correspond to the levels of Knudsen's 'sea state zero' (Ross 1976) extended to low frequencies.

case. The characteristics of each of these types of industrial noise are described in later sections.

Boat and Ship Noise

Sounds from a wide range of boat and ship types were recorded during 1980 and 1981. The two small vessels whose sounds were studied were the 'Sequel' and the 'Imperial Adgo'. Two moderate-sized vessels whose sounds were recorded were the 'Canmar Supplier VIII' and the 'Canmar Supplier III'. We also recorded the noise from a large self-propelled hopper dredge, the 'Geopotes X', that passed our vessel on one occasion.

Boat Noise--'Sequel'

The 'Motor Vessel Sequel' is a former west coast fishing boat chartered by our project during August 1981. She was used in support of the disturbance trials and feeding studies as well as for sound recording. Because of her role in the disturbance trials (see Fraker et al. 1982), her sounds are of interest.

'Sequel' is 12.5 m long. She is powered by a Detroit Diesel 471 engine having 4 cylinders, 71 cu in/cylinder. A 2.5:1 reduction gear couples the engine to the single propeller shaft. The propeller has three blades, is 81.3 cm in diameter, and has a pitch of 71.1 cm. Normal cruise is 8.3 knots (15.4 km/h) with the engine running at 1650 rpm. These propulsion characteristics would be expected to produce tonal components at 110 Hz for the cylinder firing rate and 33 Hz for the blade rate.

We never measured the radiated noise from 'Sequel' purposefully. She was at anchor or drifting with the engine off whenever noises of other sources were being recorded from on board. However, 'Sequel' signals were received on a sonobuoy while she was underway during a boat disturbance experiment on 25 August 1981. The location was 69°52'N, 134°48'W and the water depth was 11 m. The distance between 'Sequel' and the sonobuoy is not accurately known, but was about 3 km based on an estimate from the Islander aircraft. The period of maximum boat noise was several minutes in duration.

An analysis of signals recorded at 12:55 MDT is presented in Figure 7. The first tone occurs at 30 Hz, which is close to the blade rate predicted for an engine speed of 1650 rpm. The corresponding 'bang rate' (cylinder firing rate) would be 100 Hz, but the closest tone occurs at 108 Hz. A tone at 60 Hz may be the second harmonic of the blade rate. The spectrum peaks broadly around 460 Hz. 'Sequel' is the only vessel analyzed during this project whose spectrum climbs notably to such a high frequency before beginning to fall off. Figure 7A indicates a series of broad maxima centered at approximately 270, 350, and 460 Hz. This series continues with maxima at 560 and 670 Hz. The maximum level (at about 460 Hz) is 36 dB greater than the expected value at that frequency in sea state zero (Ross 1976).

Boat Noise--'Imperial Adgo'

The 'Imperal Adgo', a 16.1-m crew boat capable of 22 knots (41 km/h), was used to experimentally disturb bowheads on 27 August 1980 (see 'Disturbance' section, Fraker et al. 1982). A sonobuoy was deployed near the bowheads in order to monitor the boat noise to which they were exposed. In this section, we report the waterborne noise as the 'Adgo' moved past the whales and sonobuoy, and as it idled (with motor disengaged) 3.7 km away. The sonobuoy was dropped at 70°01'N and 132°06'W at 13:19 MDT. The water depth determined from hydrographic charts was 18.5 m, and the hydrophone was at 18 m. The two 8-cylinder, 2-cycle General Motors diesel engines of the 'Imperial Adgo' run at 2100 rpm for full speed. There is a 2:1 reduction gear box, and each propeller has 3 blades.

The test with the strongest received tonal levels (see Fraker et al. 1982; Table 2, episode 3) resulted in the graphs in Figure 8. The strongest tone (112.8 dB//1 μPa*) was at 90 Hz. This appears to be the second harmonic in a family; other members may be seen at 46 and 136 Hz. Other peaks occurred at 186, 326, and 420 Hz. Figure 8B shows a staircase effect which is unexplained. The levels at all frequencies are considerably above the quiet ambient levels reported in Figure 5. For example, the level at 1000 Hz is 29 dB higher, that at 2000 Hz is 19 dB higher, and that at 4000 Hz is 19

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* The value is higher than is evident on the corresponding Figure because the value shown on the Figure is a spectrum level computed presuming a broadband signal.

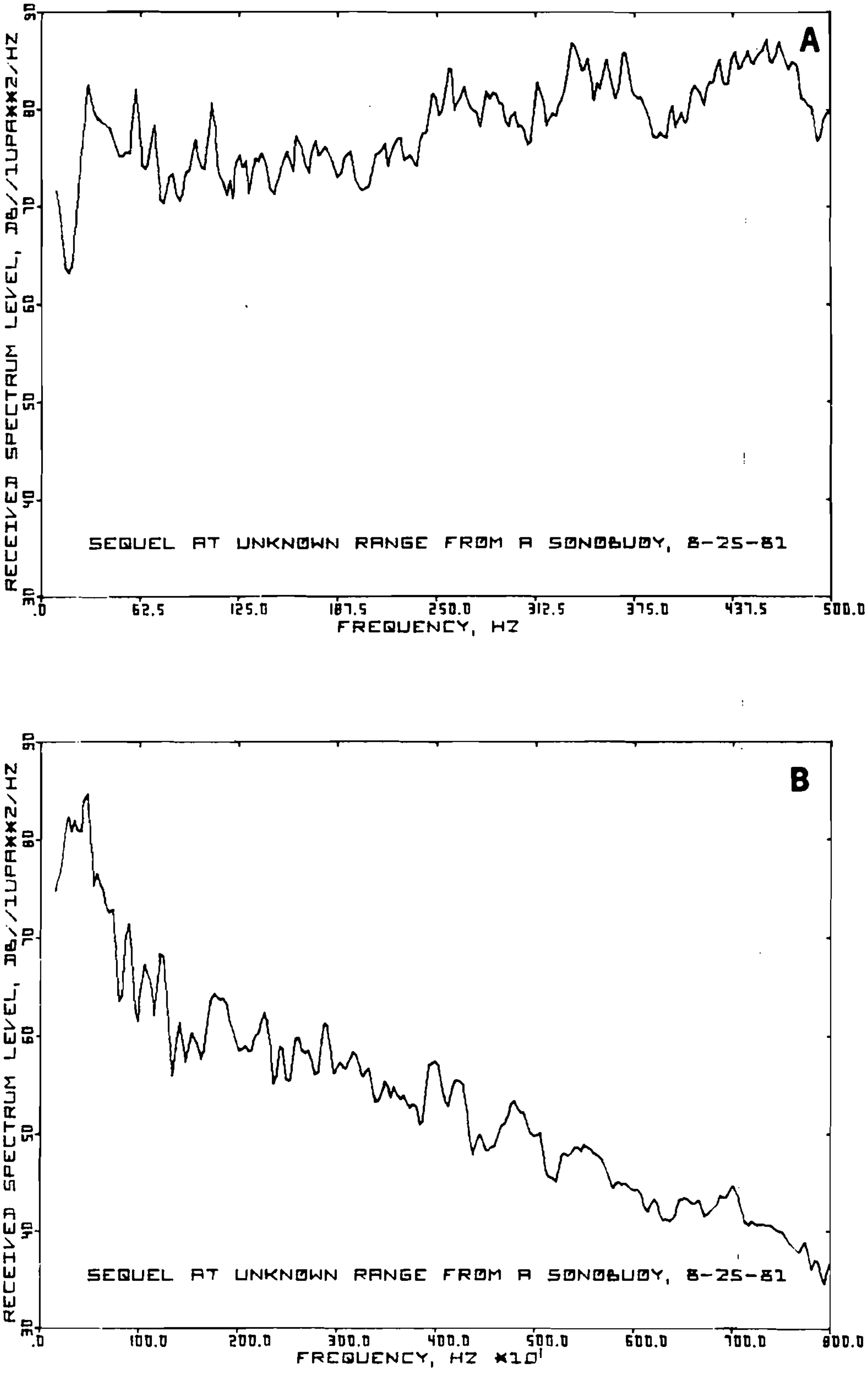

FIGURE 7. Averaged spectra of 'Sequel' noise received at a sonobuoy at an unknown range, probably about 3 km. **(A)** spans frequencies from 10-500 Hz and is averaged over 4 s. **(B)** spans frequencies from 160-8000 Hz and is averaged over 1 s.

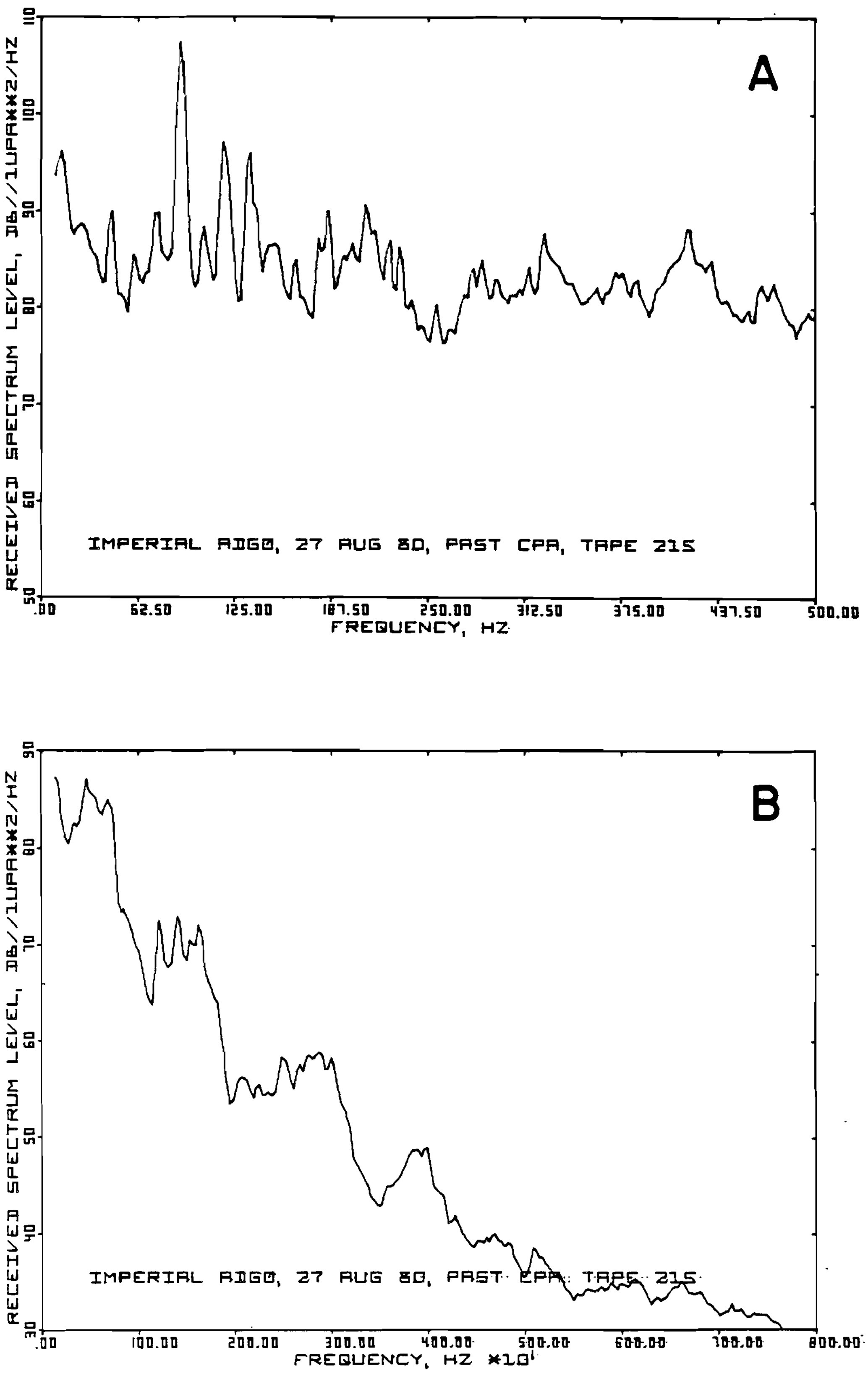

FIGURE 8. Averaged spectra for the 'Imperial Adgo' (a 16.1 m crew boat) at stern aspect during a bowhead disturbance trial. **(A)** Low frequency analysis (10-500 Hz); averaging time 16 s. **(B)** Broadband analysis (10-8000 Hz); averaging time 1 s. CPA = closest point of approach.

dB higher. The spectrum levels in Figure 8 are believed to have been measured at a time just following CPA (closest point of approach). Therefore the aspect of the source vessel was stern aspect, or at least the stern quarter. The distance from the boat to the sonobuoy at CPA was estimated as 200 m.

Another run past the sonobuoy (episode 5 of the disturbance trial) was made later on the same day, but with CPA somewhat farther away (about 400 m) than in the case just reported. Graphs of spectrum levels for this second run are shown in Figure 9. In Figure 9A a 50 Hz family can be seen, suggesting a somewhat higher operating speed than was used in the earlier run. The fundamental frequency has the highest level, 105.7 dB//1 μPa*. In the higher frequency band (Fig. 9B), the 1000 Hz broadband level is seen to be about 67 dB, or 27 dB higher than the ambient values reported above. The 2000 Hz level is 55 dB, or 20 dB higher than ambient; and the 4000 Hz level is 42 dB, or 12 dB above ambient. The staircase effect seen in the previous run (Fig. 8B) is not manifest in this analysis, although there is a slight 'hump' in the spectrum near 4000 Hz.

Two spectra for the 'Adgo' idling at a distance of about 3.7 km from the sonobuoy are shown in Figure 10. The low-frequency band in Figure 10A shows only two distinctive tones, at 72 and 102 Hz, and they are not particularly strong. The 100 Hz broadband level of about 76 dB is considerably higher than the previously reported ambient level of 52 dB. The high-frequency levels during idling at a distance of 3.7 km are considerably lower than for the running vessel at a lesser distance--only 9 dB above the ambient level at 1000 Hz, and near the ambient level at 8000 Hz. However, the 'hump' near 4000 Hz is far more pronounced than for the running vessel.

Boat Noise--'Canmar Supplier III'

A fleet of supply vessels supports the drillships and artificial island sites throughout the eastern Beaufort Sea during the open-water season of the summer. When 'Sequel' was anchored near the drillship 'Explorer II' to measure its sounds (see below), 'Supplier III' was tied along the port side

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* Higher than value evident on Fig. 9A because latter is converted to spectrum level.

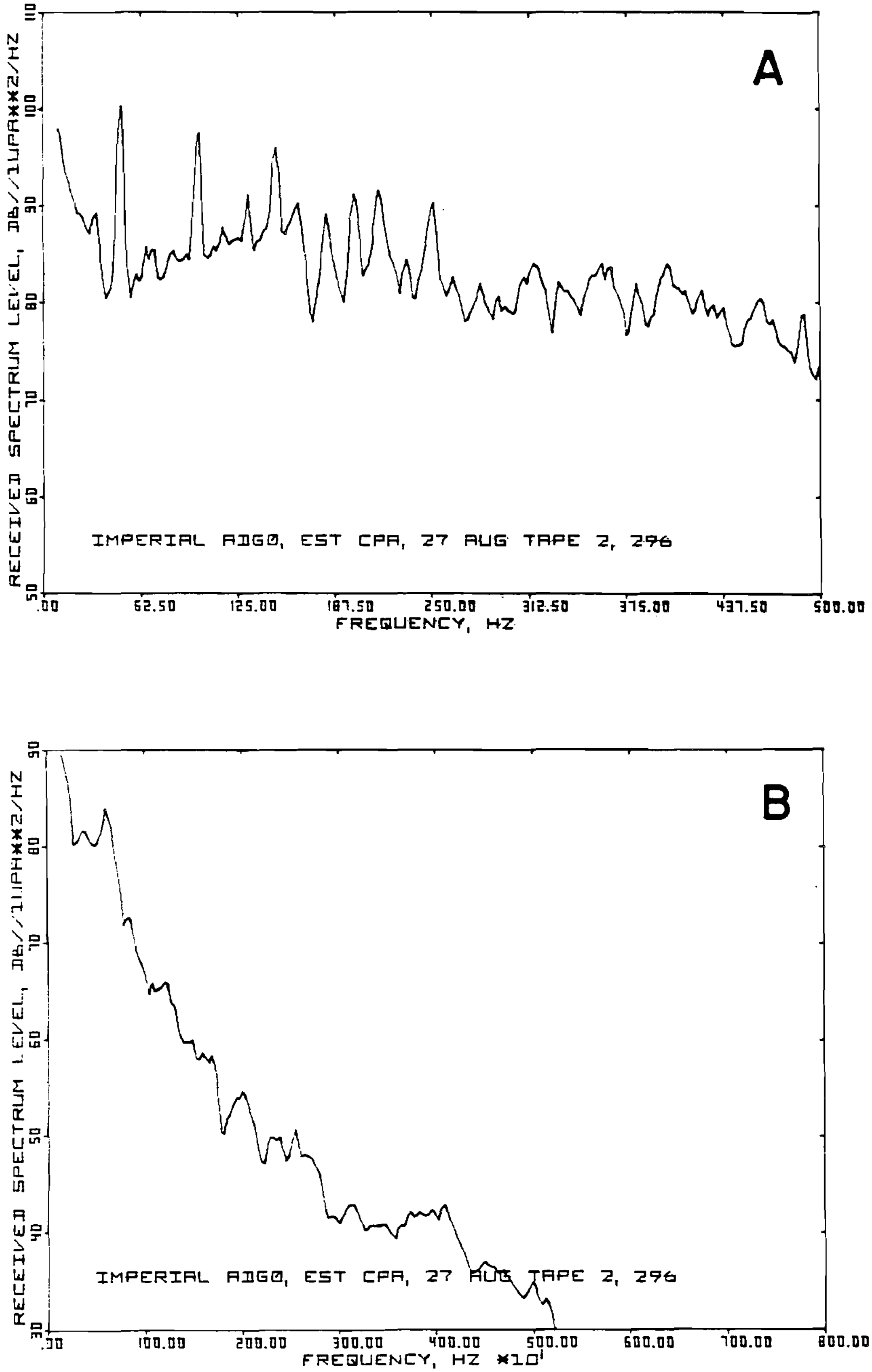
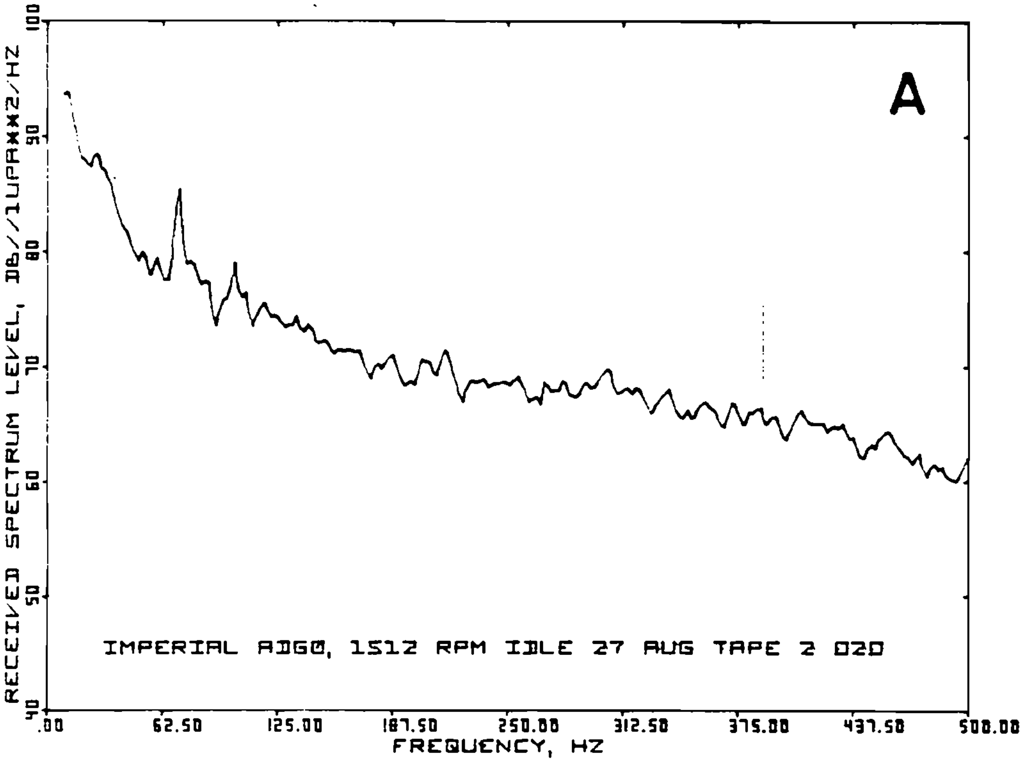


FIGURE 9. Averaged spectra for the 'Imperial Adgo' at the closest point of approach during a bowhead disturbance trial. **(A)** Low frequency analysis (10-500 Hz); averaging time 16 s. **(B)** Broadband analysis (160-8000 Hz); averaging time 1 s.



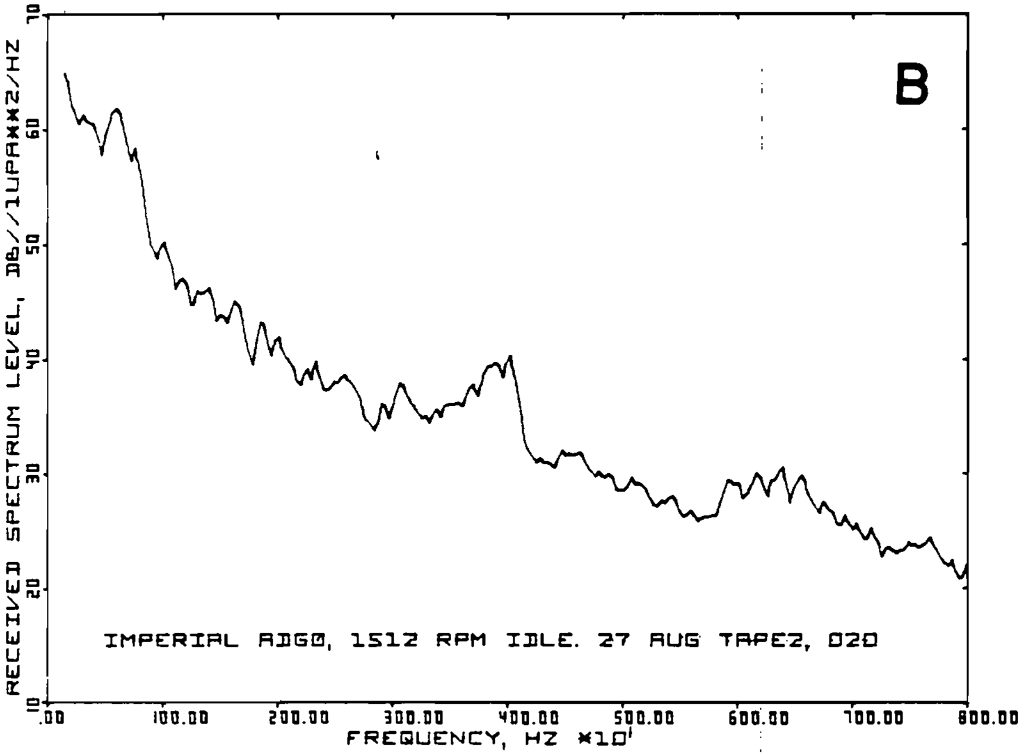


FIGURE 10. Averaged spectra for the 'Imperial Adgo' idling at a distance of about 3.7 km. **(A)** Low frequency analysis (10-500 Hz); averaging time 16 s. **(B)** Broadband analysis (160-8000 Hz); averaging time 1 s.

of the drillship. 'Sequel' was anchored at a range of 185 m on the port quarter. The tape recorders were running when 'Supplier III' started her transverse bow thruster to pull away from 'Explorer II'. The mooring lines from the drillship restrict the maneuvering space and the transverse thruster permits the bow to pull away smartly until the supply vessel is pointed directly away from the drillship.

'Supplier III' displaces 1270 long tons, is 65 m long, 15 m wide, and is powered by two engines developing a total of 7200 shaft horsepower. The bow thruster is powered by a 450 hp motor. Essentially the only sounds from 'Supplier III' that we recorded came from the bow thruster, because after completing the turn away from 'Explorer II' the supply vessel secured the bow thruster and proceeded at slow speed.

Figure 11 presents averaged spectra for the startup sounds for two frequency bands: 10-500 Hz and 160-8000 Hz. The strongest tone (129.3 dB//1 μPa) was at 236 Hz, which is the second harmonic in the family whose fundamental is at 118 Hz. The harmonics remained strong through the ninth at 1070 Hz (122.4 dB//1 μPa). This bow thruster signal ranks among the strongest signals recorded during the project.

Figure 12 presents two spectrograms for the 'Supplier III' bow thruster. The tape recorder gain was reduced shortly after the thruster started to prevent distortion of the recorded signal (the gain had been set for the drillship noises). Thus, the 'waterfall' spectrogram display presents data recorded only after the gain change. The intensity-modulated spectrogram illustrates the complete sequence of frequency changes during startup.

Boat Noise--'Canmar Supplier VIII'

Noise from another Dome/Canmar supply vessel was recorded on 7 August 1980 from the sailing vessel 'Ungaluk' while drifting at 70°22'N, 134°55'2. There was no operating radar on 'Ungaluk' so ranges had to be estimated by eye. Such estimates are subject to serious error, especially over water. Water depth was 46 m. 'Ungaluk' was about 2.5 km from the drillship 'Explorer I' when the 'Canmar Supplier VIII' passed at an estimated range of <200 m.

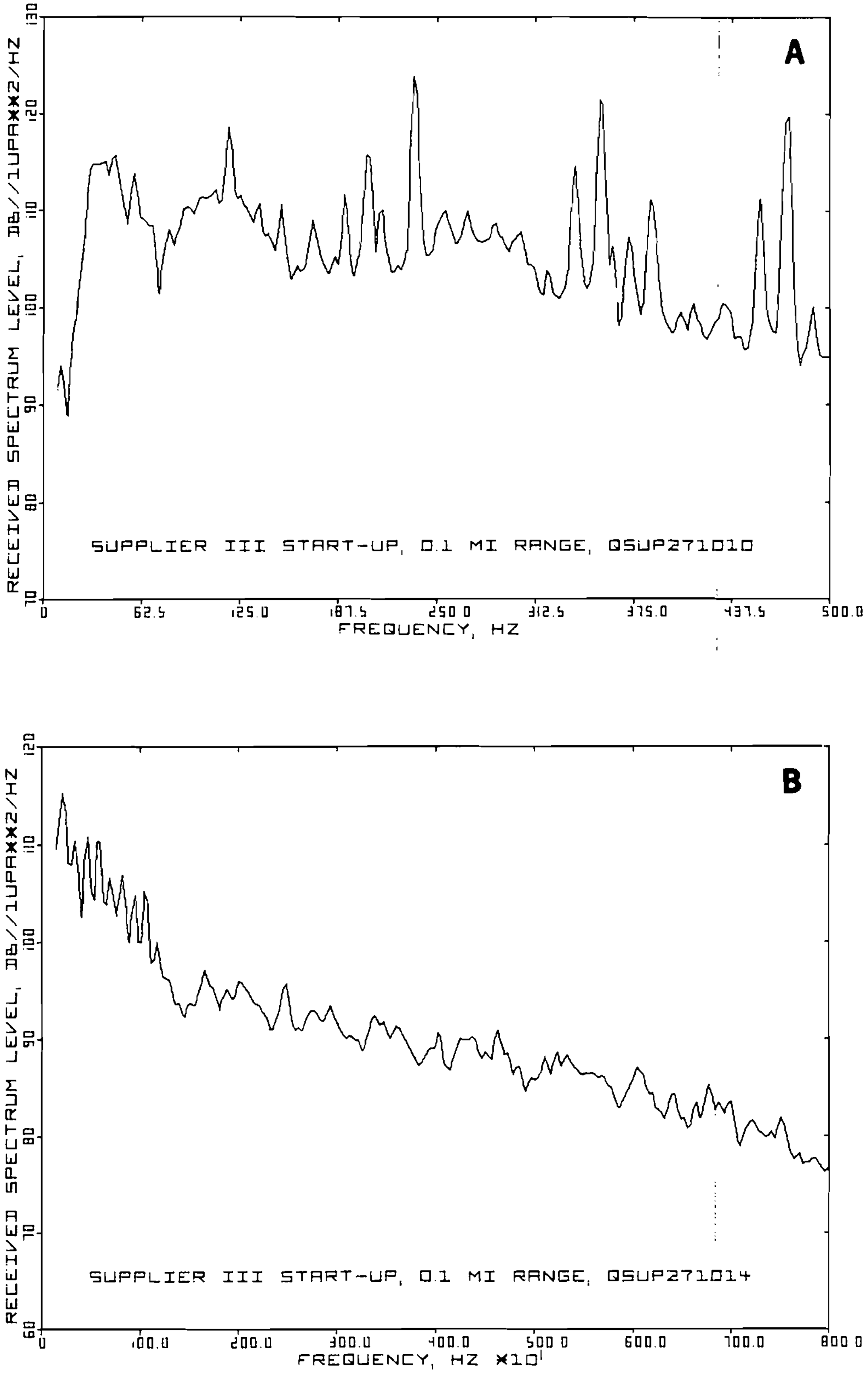


FIGURE 11. Averaged spectra for 'Canmar Supplier III' at a range of 0.1 n.mi. (185 m) while operating her bow thruster during initial departure from drillship 'Explorer II'. **(A)** is for frequencies from 10 to 500 Hz; averaging time 16 s. **(B)** is for frequencies from 160 to 8000 Hz; averaging time 1 s.

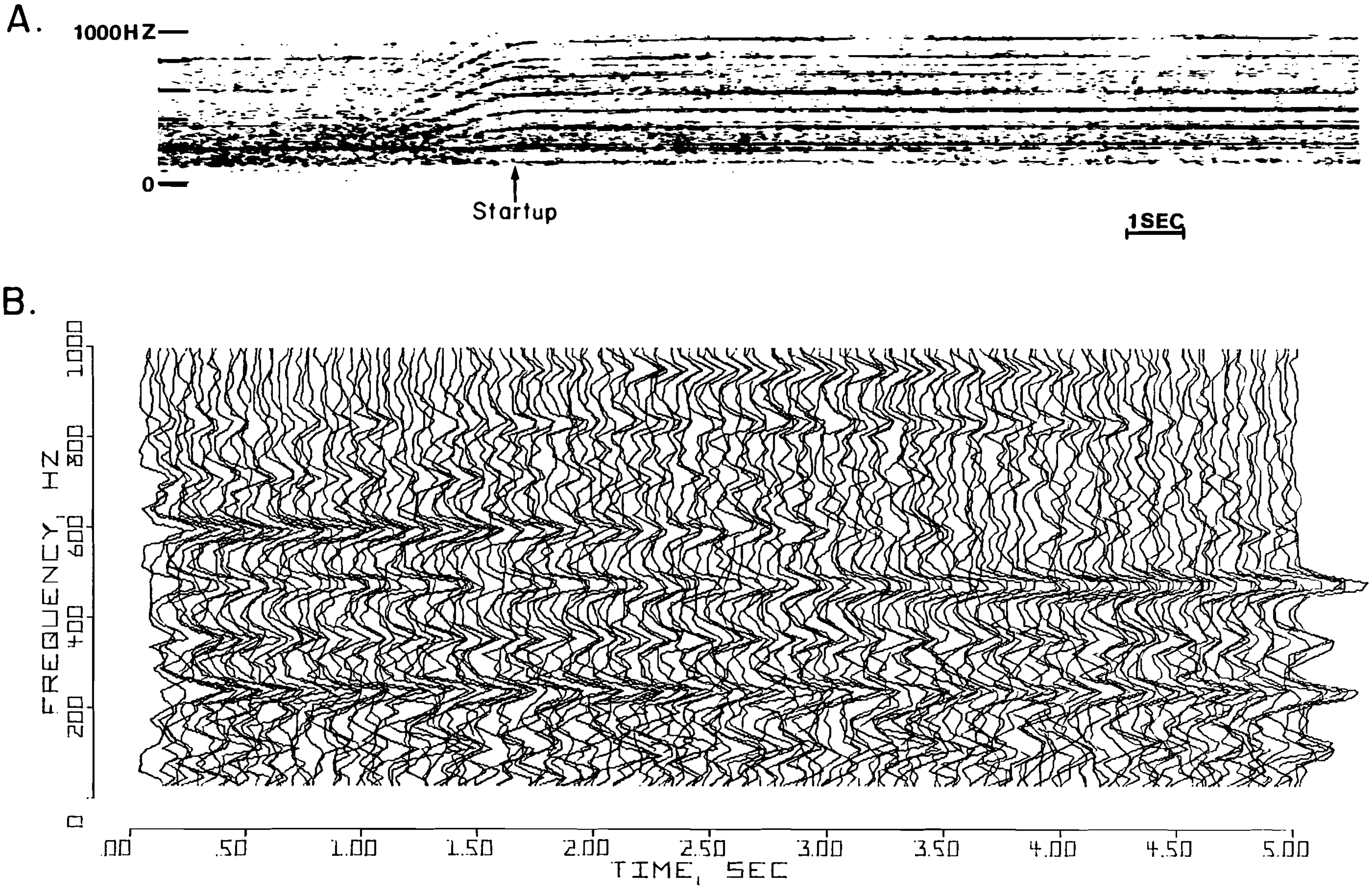


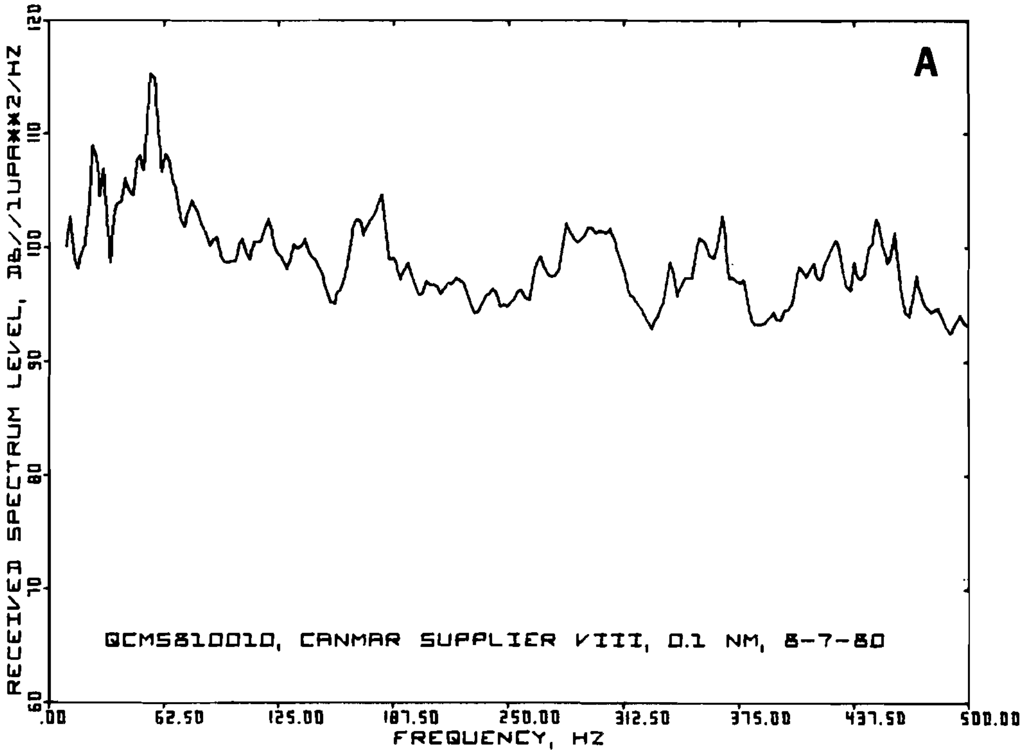
FIGURE 12. Spectrograms for the bow thruster on 'Canmar Supplier III' at a range of 0.1 n.mi. (185 m) during initial departure from drillship 'Explorer II'. **(A)** Intensity-modulated spectrogram before, during and after start up. **(B)** 'Waterfall' display after startup.

Figure 13 presents averaged spectra for 'Supplier VIII' noise at an estimated range of 0.1 n.mi. or about 185 m. The strongest tone is at 56 Hz at a level of 120.7 dB//1 μPa. This vessel has two 12-cylinder, 4-cycle engines whose combined power is 2200 shp. Each engine drives a four-bladed propeller through a reduction gear of 3.7:1. Attributing the 56 Hz tone to the blade rate results in an engine speed of 3108 rpm, far above the stated normal operating speed of 1225 rpm. Attributing the 56 Hz tone to the 'bang rate' of the diesels results in an engine speed of 560 rpm (and a blade rate of 10 Hz). This is possible if 'Supplier VIII' was slowing as it approached 'Explorer I', but my recollection is that the supply ship continued past 'Ungaluk' at what seemed a normal speed until within about 1 km of the drillship, when she slowed to a stop. The normal speed of 'Supplier VIII' is said to be 19.5 km/h for an engine speed of 1225 rpm. (The corresponding blade rate would be 22 Hz.)

Figure 14 presents two spectrograms of the sounds from 'Supplier VIII'. A harmonic family may be seen in the spectrograms. Its fundamental tone occurs at approximately 156 Hz, but its source is unidentified. The two dark 'blobs' on the intensity-modulated spectrogram correspond to distant seismic survey signals. They are almost 13 s apart, which is significantly longer than the typical 8 to 10 s between firings of the sleeve exploders on 'Arctic Surveyor'. Thus they may have come from airguns on a different vessel. The data for the 'waterfall' spectrogram were taken between seismic survey signals.

Hopper Dredge--'Geopotes X'

While 'Sequel' was anchored at 70°02'N, 133°56'W waiting for the helicopter to arrive for noise measurements, a vessel travelling at 24 km/h appeared from over the horizon. After a time it became clear that she was the 'Geopotes X', a self-propelled hopper dredge, fully loaded, and that she was headed directly for us. 'Geopotes X' is 136 m long, 22 m wide, draws 4 m empty and 12 m full, and displaces 17,981 tons. The noise was remarkable and we started the recorder. Ranges were read from the radar on 'Sequel'. Water depth was 25 m and the H56 hydrophone was suspended at 9 m. Because 'Geopotes X' was traveling rather than dredging, we discuss her noise in the present 'ship noise' section rather than under 'dredge noise'.



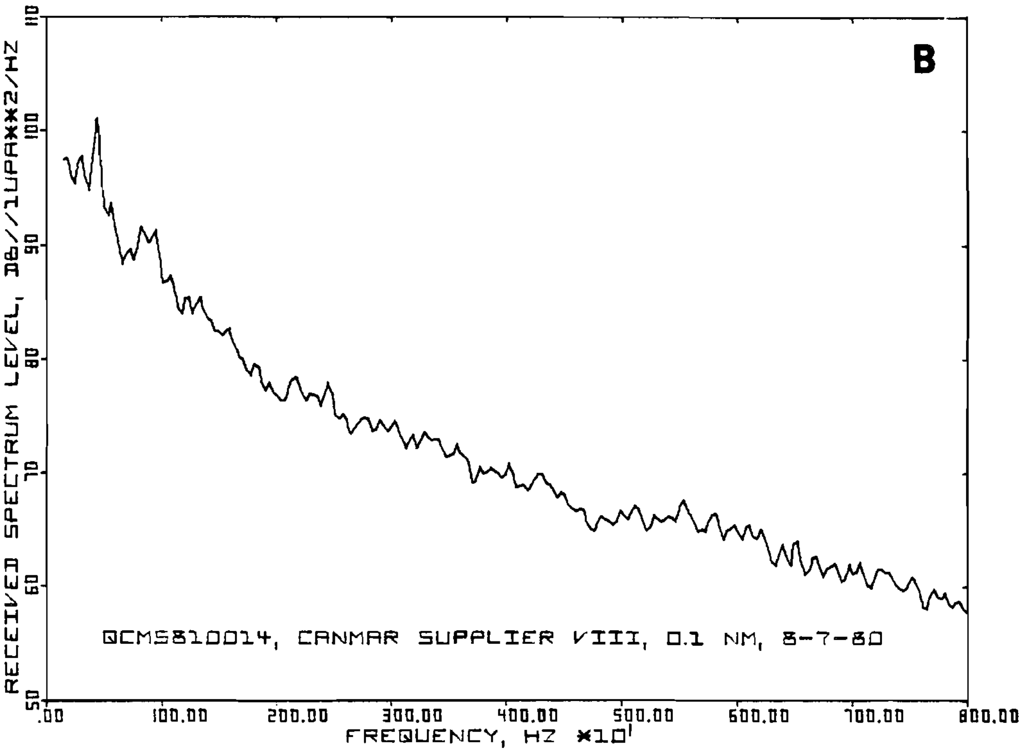


FIGURE 13. Averaged spectra for 'Canmar Supplier VIII' at an estimated range of 0.1 n.mi. (185 m). **(A)** spans frequencies from 10 to 500 Hz; averaging time 16 s. **(B)** spans frequencies from 160 to 8000 hz; averaging time 1 s.

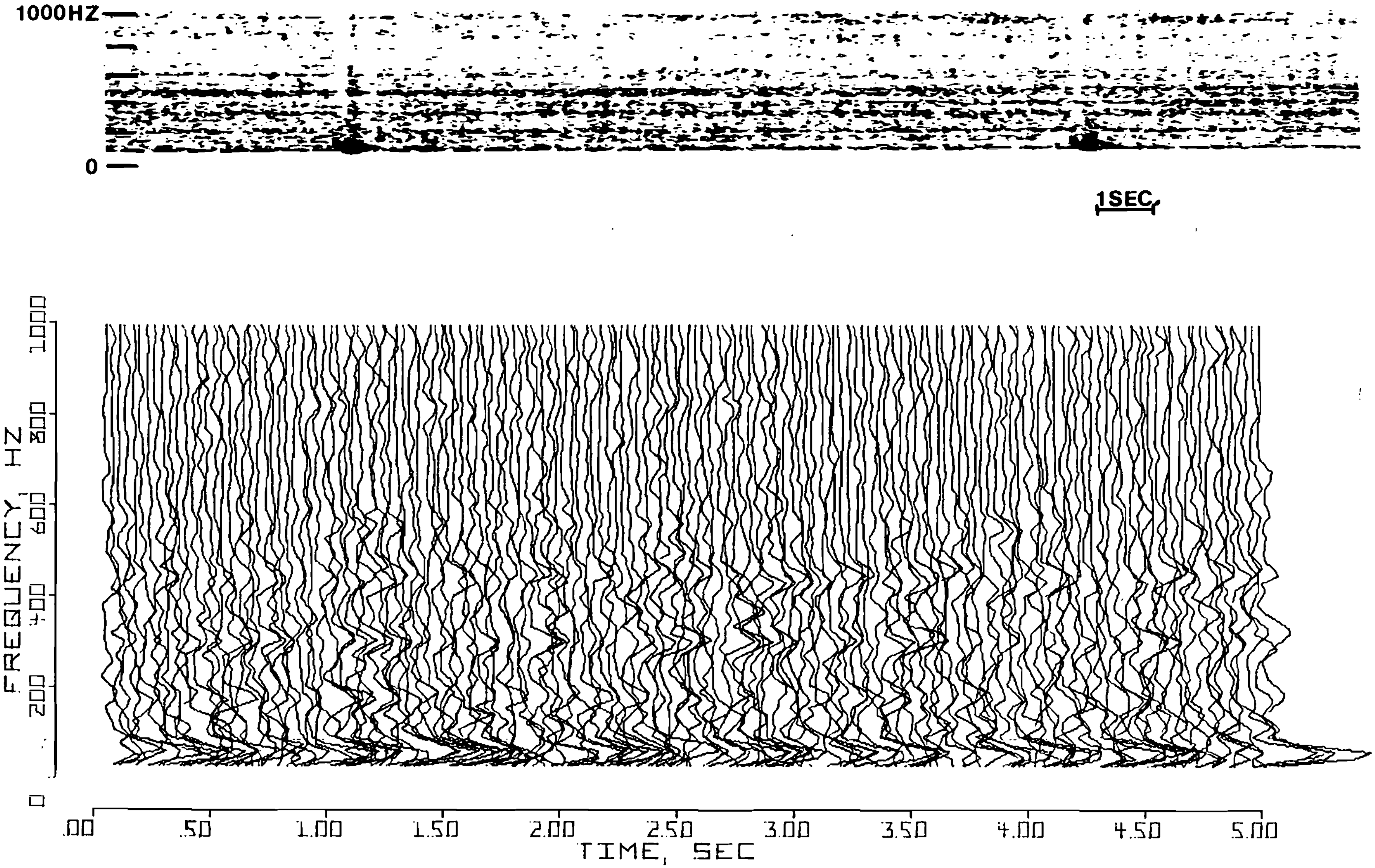


FIGURE 14. Spectrograms for 'Canmar Supplier VIII' at an estimated range of 0.1 n.mi. (185 m). The two dark 'blobs' on the intensity-modulated (upper) spectrogram correspond to seismic survey signals from a distant source.

Although a change in heading was never observed, the vessel missed us by 0.1 n.mi. (185 m). With the post amplifier and tape recorder gains set as low as possible without taking time to alter the internal wiring, the record levels exceeded the 'red line' until the range opened to 0.25 n.mi. (463 m). 'Geopotes X' provided the highest levels of any non-impulsive industrial noise source measured during the two summers of field work in the eastern Beaufort Sea.

Figure 15 contains average spectra for 0.25 n.mi. (463 m), opening range. Generally, the received levels were higher for the stern aspect than for the bow aspect for any given range. Minor peaks in the spectrum appear at 412 and 470 Hz, but the dominant peak is at 72 Hz. The low frequency spectrum shown in Figure 15A is the result of averaging 64 overlapping spectra computed from 16 seconds' data, and the frequency fluctuations over that period of time caused the average to be wider than it would appear in the individual spectra. Figure 16, spectrograms for 'Geopotes X' at 0.25 n.mi., illustrates the variability of the strongest tones. Note that the minor peaks at 412 and 470 Hz do not appear.

Figure 17 contains average spectra for 4.0 n.mi. (7.4 km), opening range. The strongest peak occurs at 80 Hz, a smaller peak occurs at 472 Hz, and a strong peak (relative to the adjacent continuous spectral levels) occurs near 1000 Hz. In fact, although it did not appear in the 160-8000 Hz spectrum in Fig. 15, the peak near 1000 Hz appeared in the 40-2000 Hz spectra for all six ranges analyzed.

We analyzed received levels vs. range for both the near 1000 Hz tone and the dominant peak near 80 Hz. We say 'near 80' because it varied from 70 to 92 Hz over the six ranges used in the analysis (0.25, 0.5, 1.0, 2.0, 3.0, and 4.0 n.mi.). The measured levels were taken from the 40-2000 Hz spectra because these were averaged over only 4 s and the analysis width was 13.7 Hz, thereby allowing somewhat for the variability. The near 1000 Hz tone was constant in frequency, occurring at 1008 Hz.

For the near 1000 Hz tone, a general regression analysis resulted in the following equation:

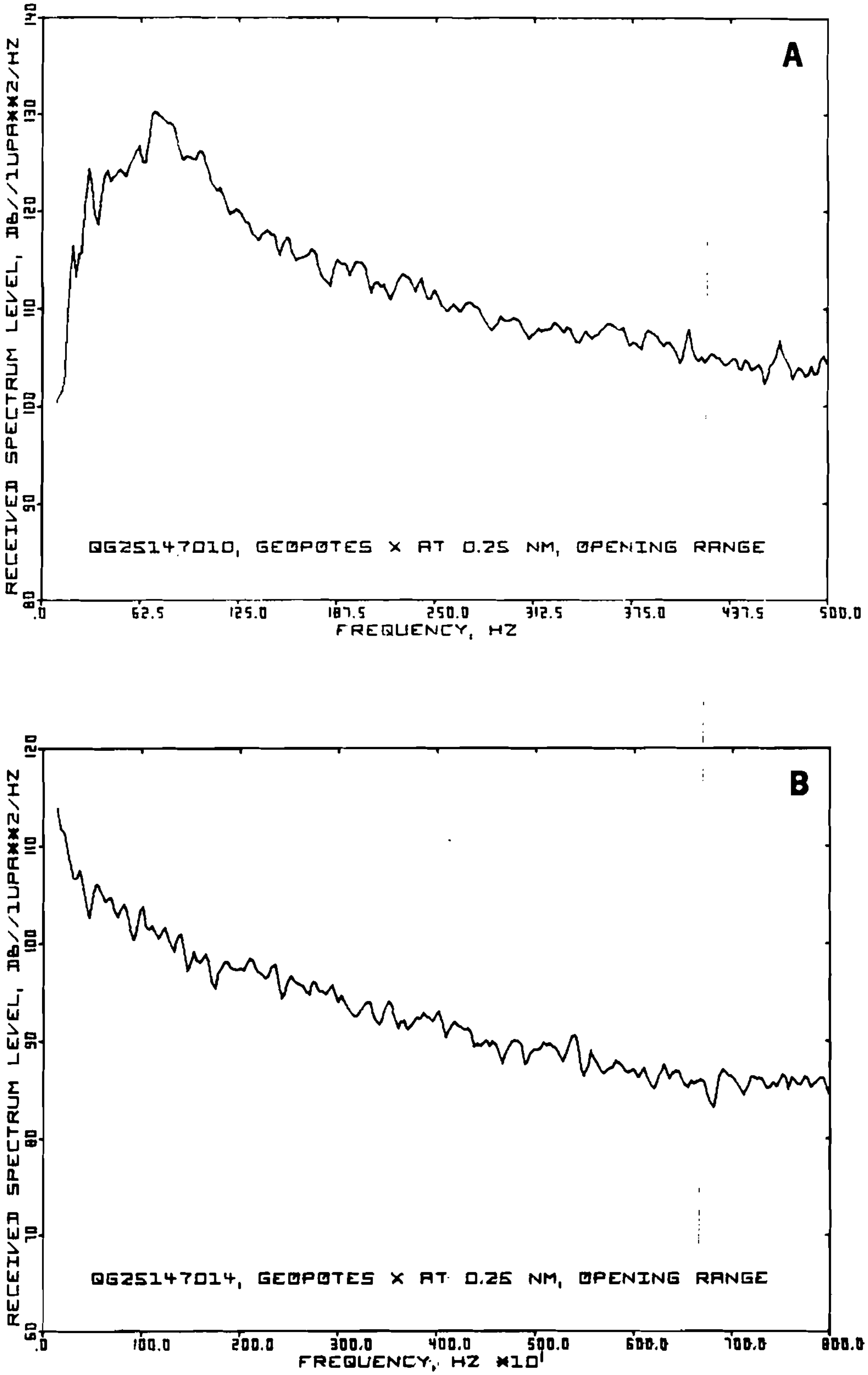


FIGURE 15. Averaged spectra for hopper dredge 'Geopotes X' at 0.25 n.mi. (463 m), underway and opening range. **(A)** is for low frequencies (10-500 Hz); averaging time 16 s. **(B)** is for a broad range of frequencies (160-8000 Hz); averaging time 1 s.

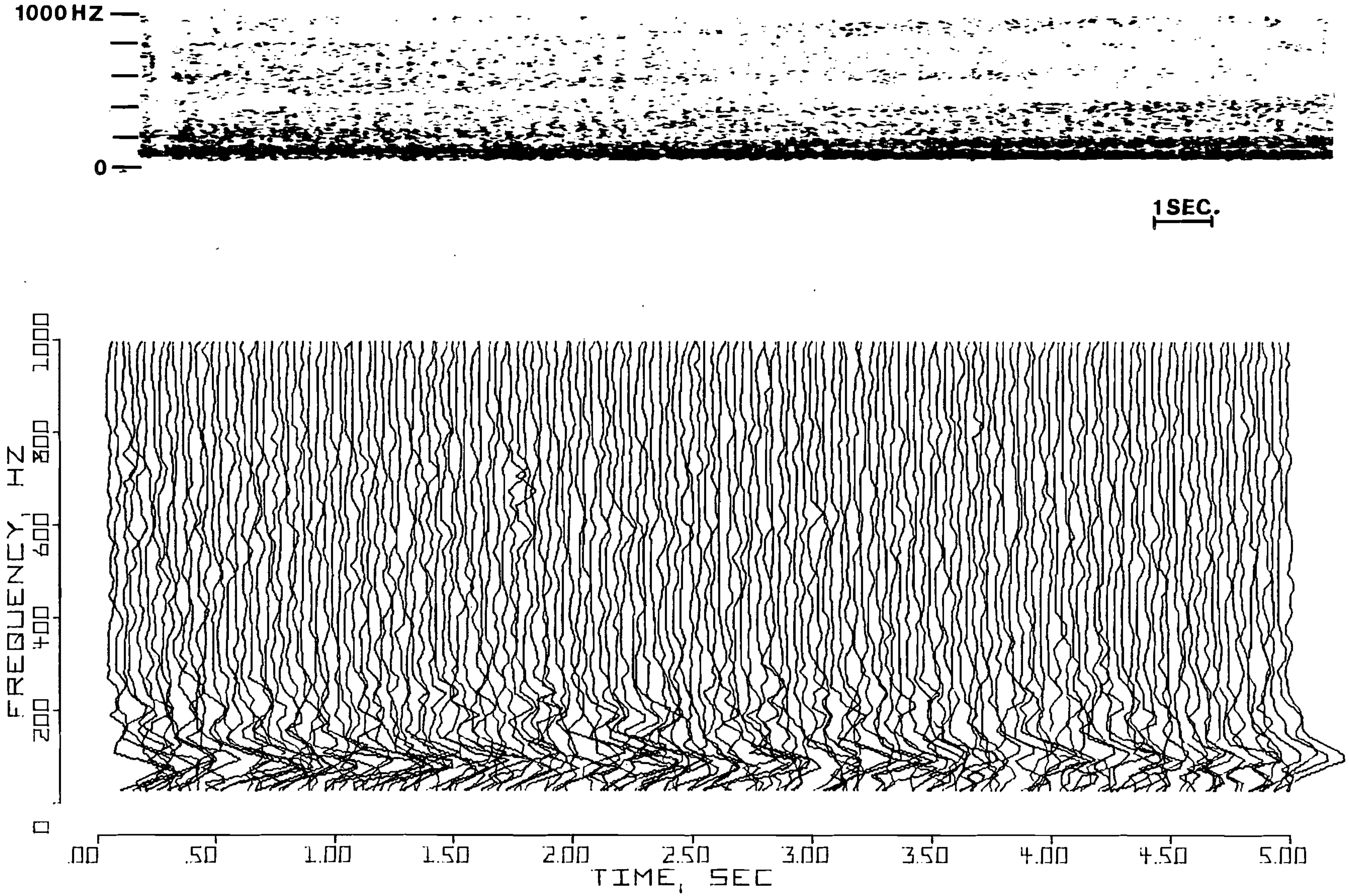


FIGURE 16. Spectrograms of the hopper dredge 'Geopotes X' at 0.25 n.mi. (463 m), underway and opening range.

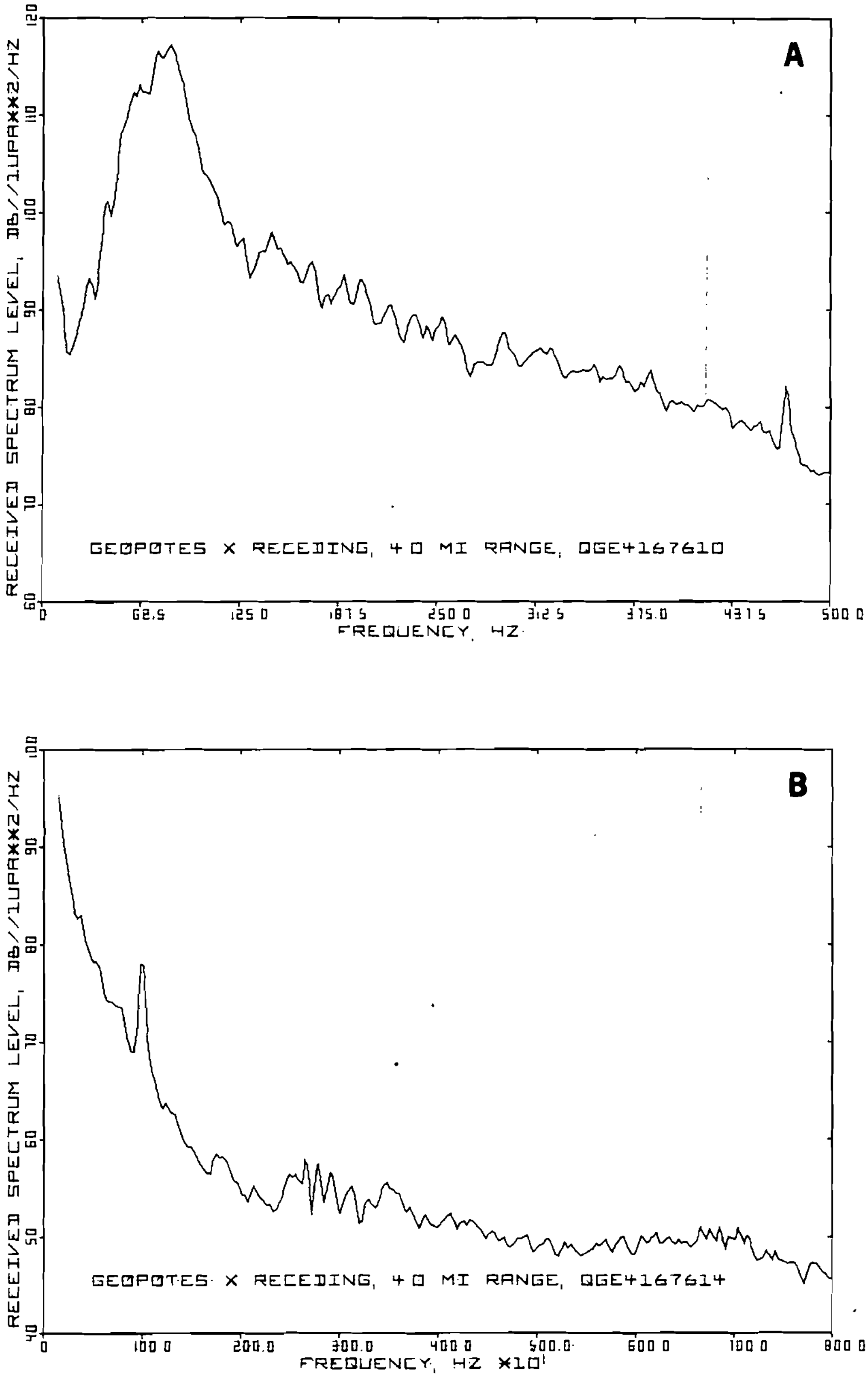


FIGURE 17. Averaged spectra for hopper dredge 'Geopotes X' at 4.0 n.mi. (7.4 km), underway and opening range. **(A)** is for low frequencies (10-500 Hz); averaging time 16 s. **(B)** is for a broad range of frequencies (160-8000 Hz); averaging time 1 s.

$$RL\ (\text{in dB//1 } \mu Pa) = 117.5 - 0.831*R - 20.59*\log(R)$$

where RL is the received level, R is in kilometres, and the logarithm is to the base 10. The standard error was 2.57 dB and the coefficient of determination was 0.972. This equation contains a linear term corresponding to absorption loss in addition to a log (R) spreading loss term. The linear term provides for a loss of some number of dB per kilometre. Considering a sound ray path model of sound propagation, the sound rays bounce continually between the bottom and the surface enroute from source to receiver. Absorption by the bottom, and possibly scattering at the surface, could account for a loss of some number of 'dB per bounce', which would be equivalent to some number of dB per kilometre.

Although the coefficient of the log(R) term was far from the 10*log(R) characteristic of cylindrical spreading, a 10*log(R) term was forced for comparative purposes and another equation computed:

$$RL\ (\text{dB//1 } \mu Pa) = 119.5 - 2.53*R - 10*\log(R).$$

For this equation the standard error was 2.88 dB and the coefficient of determination was 0.880. It is interesting to note that the 'absorption loss' term, 2.53*R, has an appreciably larger coefficient than has resulted for tones at lower frequencies (see later sections). This is consistent with the theory that higher frequencies will suffer greater 'bounce' losses. (See the discussion in the later section on sound transmission loss.)

For the strong peak at low frequency, the general regression resulted in

$$RL\ (\text{dB//1 } \mu Pa) = 136.3 - 0.131*R - 10.2*\log(R).$$

The standard error was 2.19 dB and the coefficient of determination was 0.901. When the spreading loss term was forced to be 10*log(R) for cylindrical spreading, the result was

$$RL\ (\text{dB//1 } \mu Pa) = 136.3 - 0.168*R - 10*\log(R).$$

Here, the standard error was 1.90 dB.

A comparison of the two cylindrical spreading equations for the 1000 Hz and the low frequency peaks reveals that the low frequency component was far stronger (compare the constant terms: 136.3 vs. 119.5) and that the 'absorption loss' terms are clearly frequency dependent (coefficients of 0.168 for a nominal 80 Hz vs. 2.53 for 1000 Hz).

Aircraft Noise

Noise from three types of aircraft was recorded during planned flights over hydrophones in the eastern Beaufort Sea. The three aircraft were (1) the twin engine Britten-Norman Islander used for aerial observations and studies of whale behavior, (2) a deHavilland Twin Otter, and (3) a Bell 212 helicopter. These three aircraft are examples of piston- and turbine-powered fixed-wing aircraft plus turbine-powered helicopters. Normal operating power settings were used at flyover altitudes of 500, 1000, 1500, and 2000 feet (152-610 m), although not all altitudes were obtained for all three aircraft.

Britten-Norman Islander

The Britten-Norman Islander was used to obtain recordings of aircraft noise received at a sonobuoy hydrophone. The data discussed below were collected on 23 August 1980, 10:58 MDT, at 70°07'N and 131°39'W. The water depth was determined from a hydrographic chart to be 14.5 m, and the hydrophone was on the bottom. The sea surface was calm and there were bowhead whales near the sonobuoy. Sections of recording that included whale calls are not considered here.

The aircraft's two engines were operating synchronously at a nominal 2200 rpm, 21 inches manifold pressure; this corresponds to an economy cruise power setting. With a two-bladed propeller at 2200 rpm, the blade rate would be 73.3 Hz with a harmonic family based on this frequency in the received noise spectrum. The six cylinder, four cycle, engines at the same speed would exhibit a cylinder firing rate of 110 explosions per second, and thus from this source a harmonic family based on 110 Hz would be expected in the received noise spectrum. The second and higher harmonics of 110 Hz fall at harmonics of the 73.3 Hz blade rate, and under ideal conditions one would expect those harmonics to be reinforced.

The aircraft flew over the sonobuoy at four altitudes: 500, 1000, 1500, and 2000 ft (157, 305, 457, and 610 m). Sounds recorded as the aircraft was directly overhead at each altitude were analyzed. A representative received signal spectrum level for a flyby at 1000 ft altitude is presented in Figure 18. The harmonic families predicted above are seen to be present with a blade-rate fundamental at 70 Hz, corresponding to 2100 rpm. Additional tones can be seen at 54 and 160 Hz. These tones were not present in the signature of the same aircraft computed from data recorded on 27 August 1980 and their source is unexplained.

The 70 Hz spectrum level for the case shown in Figure 18A was 85.5 dB//(1 μPa^2)/Hz. This level was obtained by 'correcting' the computed level for the effective width of the analysis filters*. However, it is not correct to report spectral density levels for pure tones; their spectral densities are theoretically infinite. Removing the 'correction' results in a received level of 93.9 dB//1 μPa for an averaging time of 8 s. Corresponding figures for the 4 s period of most intense sound were 95 and 96 dB during two passes at 1000 ft. However, the situation is further complicated by the fact that the received signal from the aircraft passing overhead was, because of Doppler shifts, not actually fixed in frequency, as would be required for a pure tone.

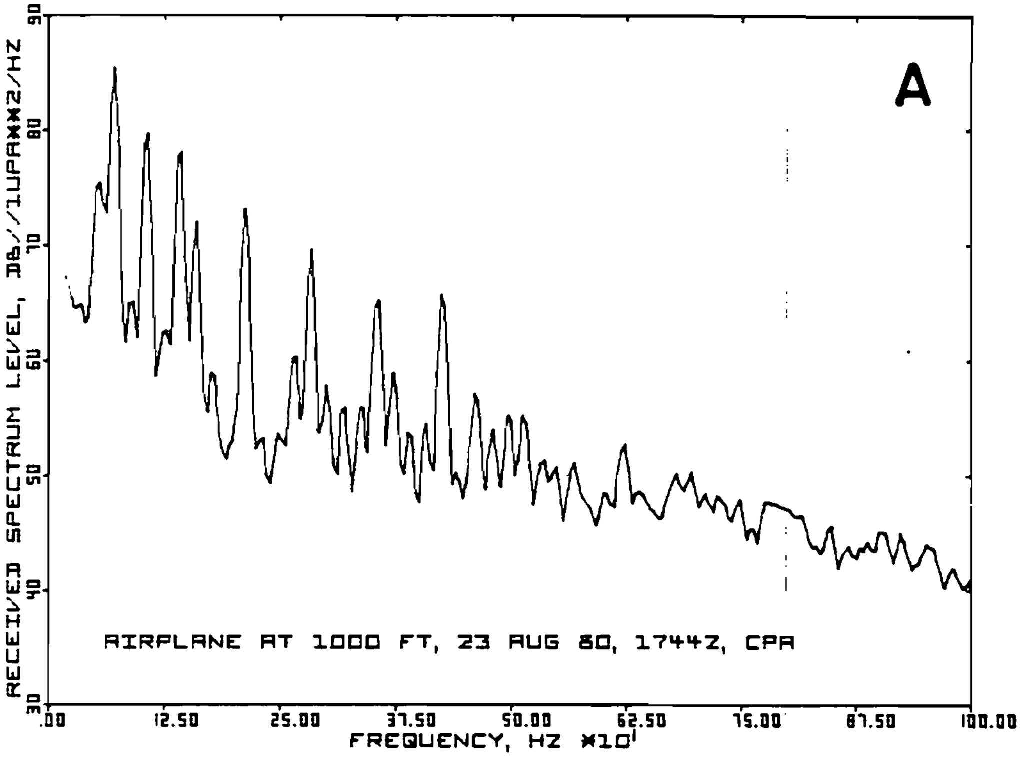
Corresponding received signal levels for the 70 Hz tone for the four heights measured were as follows:

Height	Level, dB//1 μPa, for averaging time	
	8 s	4 s
500 ft 152 m	96.6	100,102**
1000 ft 305 m	93.9	95, 96
1500 ft 457 m	92.4	93
2000 ft 610 m	97.0	96, 97

---

* In presenting these results, it is important to describe the actual analysis procedure, which was to separate the total number of samples (16,384) into 64 segments, each overlapping the previous segment by 50% and each 512 samples long; and then computing and averaging the power spectral densities for the 64 segments. Eight-seconds' data are used when 2048 samples are taken each second.

** Separate value for two passes at heights 500, 1000 and 2000 ft.



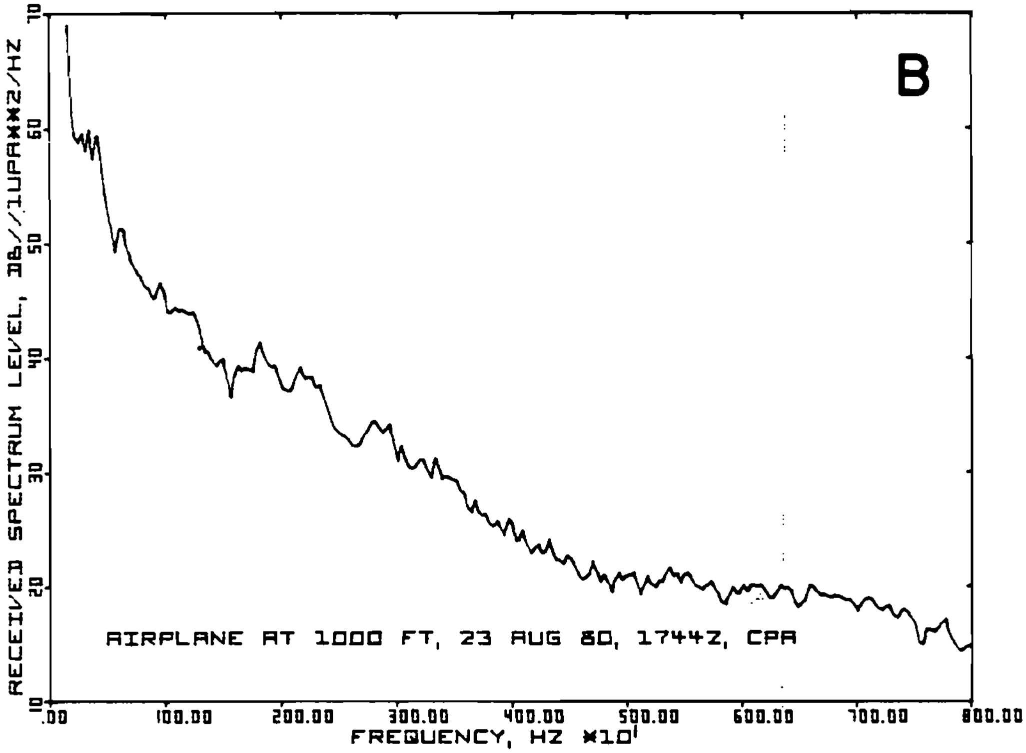


FIGURE 18. Averaged spectra for a Britten-Norman Islander aircraft flying at 1000 ft (305 m) ASL over a sonobuoy. (**A**) Low frequency analysis (20-1000 Hz); averaging time 8 s. (**B**) Broadband analysis (160-8000 Hz); averaging time 1 s. CPA = Closest Point of Approach.

The differences are not what one might expect considering that higher aircraft are more distant and therefore, for the same source level, their received signal levels might be lower. However, the physics of sound propagation between air and water explains the results to a large extent (Hudimac 1957; Weinstein and Henney 1965; Young 1973; Urick 1972; Waters 1972). Altitude-dependence of the rate of build up and decay in received level probably also affected the results; the period of peak received level was briefer than 8 s, especially during the 500 ft pass. Furthermore, Doppler changes, especially during the 500 ft pass, probably influence the results.

Spectra for the 500 ft flyby are presented in Figure 19A. The 'B' part can be compared with Figure 18B for the 1000 ft flyby; both are for 160-8000 Hz with averaging time 1 s at the time of highest received sound level. At this time of peak received level, the spectral levels for the 500 ft flyby are on the order of 20 dB higher than those for the 1000 ft flyby. Figure 20 contains spectrograms for the Islander passing over the sonobuoy at 500 ft.

Twin Otter

Twin Otters are common in arctic regions, having proven themselves as dependable freight and personnel carriers with short field capability. Although not used routinely over the Beaufort Sea in summertime except by scientists conducting aerial surveys, they are used commonly along the coast.

By special arrangement, on 6 August 1981 a Twin Otter flew over the H56 hydrophone suspended at depth 9 m behind 'Sequel' while she was anchored in 22.5 m of water 14.8 km from Issungnak Island and 21 km from the drillship 'Explorer II' (70°00.8'N, 133°56.3'W). The sea state was Beaufort 0 and the wind was calm. From notes taken by an observer on the aircraft, the air-speed was 140 knots, propeller rpm was 77%, turbine rpm was 92%, and the air temperature was 17°C. The two propellers each have three blades.

Figure 21 contains averaged spectra computed for the Twin Otter flyby at 500 ft (152 m). The fundamental tone occurs at 82 Hz. Attributing this to a blade rate, the propeller shaft rate was 1625 rpm. The small peaks at 2300

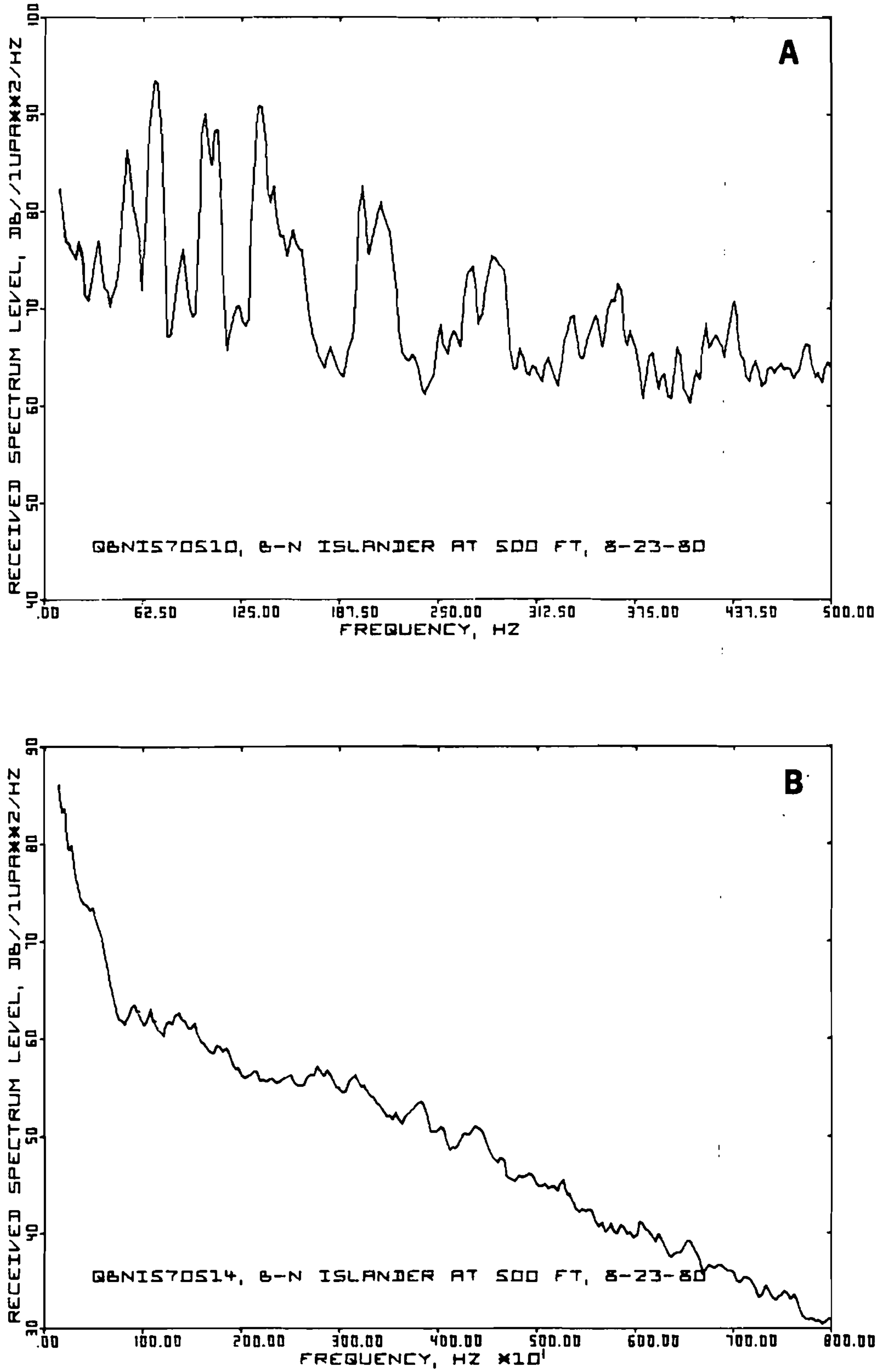


FIGURE 19. Averaged spectra for a Britten-Norman Islander aircraft flying at 500 ft (152 m) ASL over a sonobuoy. **(A)** is for 10-500 Hz; averaging time 16 s. **(B)** is for 160-8000 Hz; averaging time 1 s.

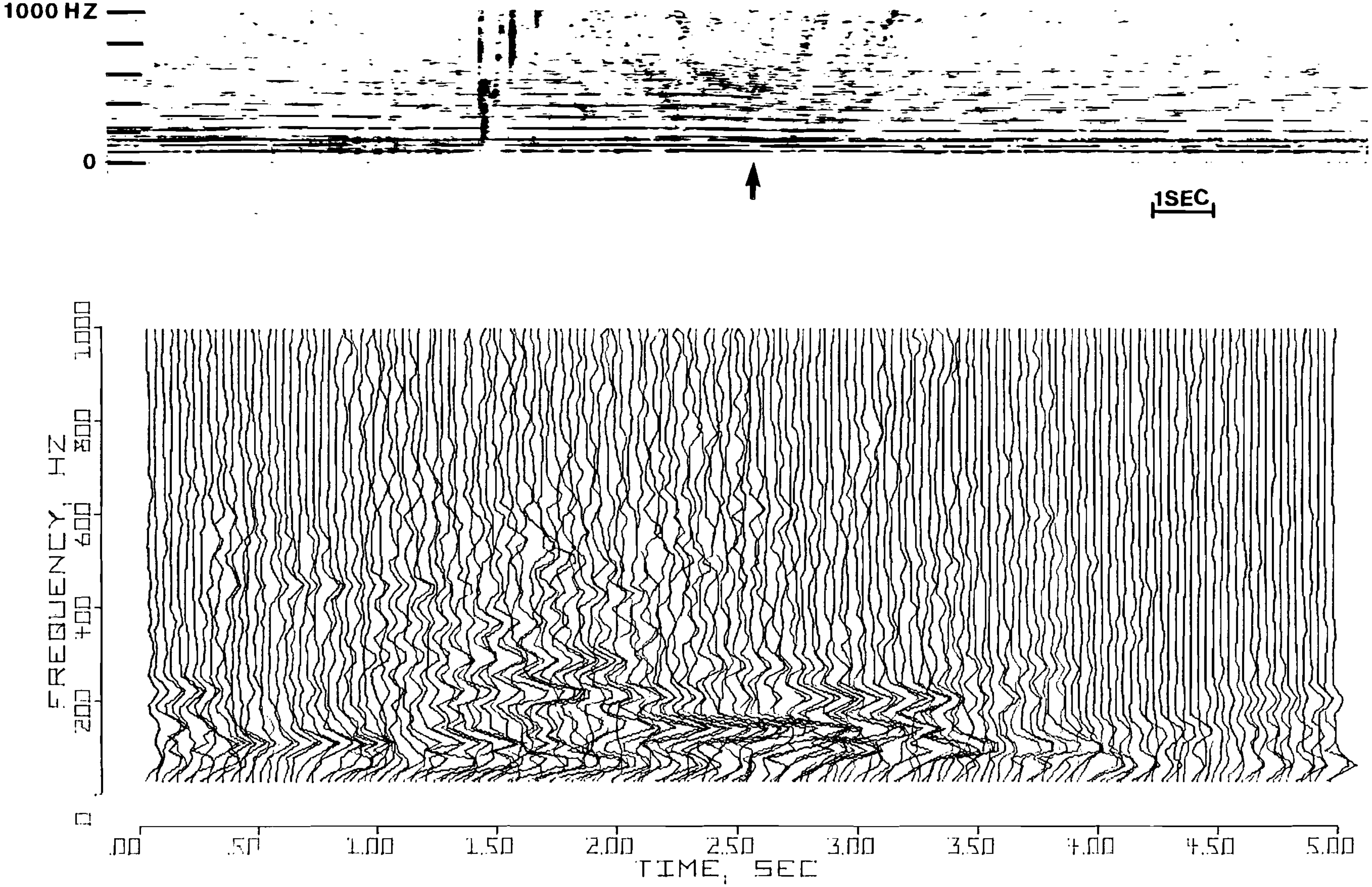


FIGURE 20. Spectrograms for a Britten-Norman Islander aircraft at 500 ft (152 m) ASL.

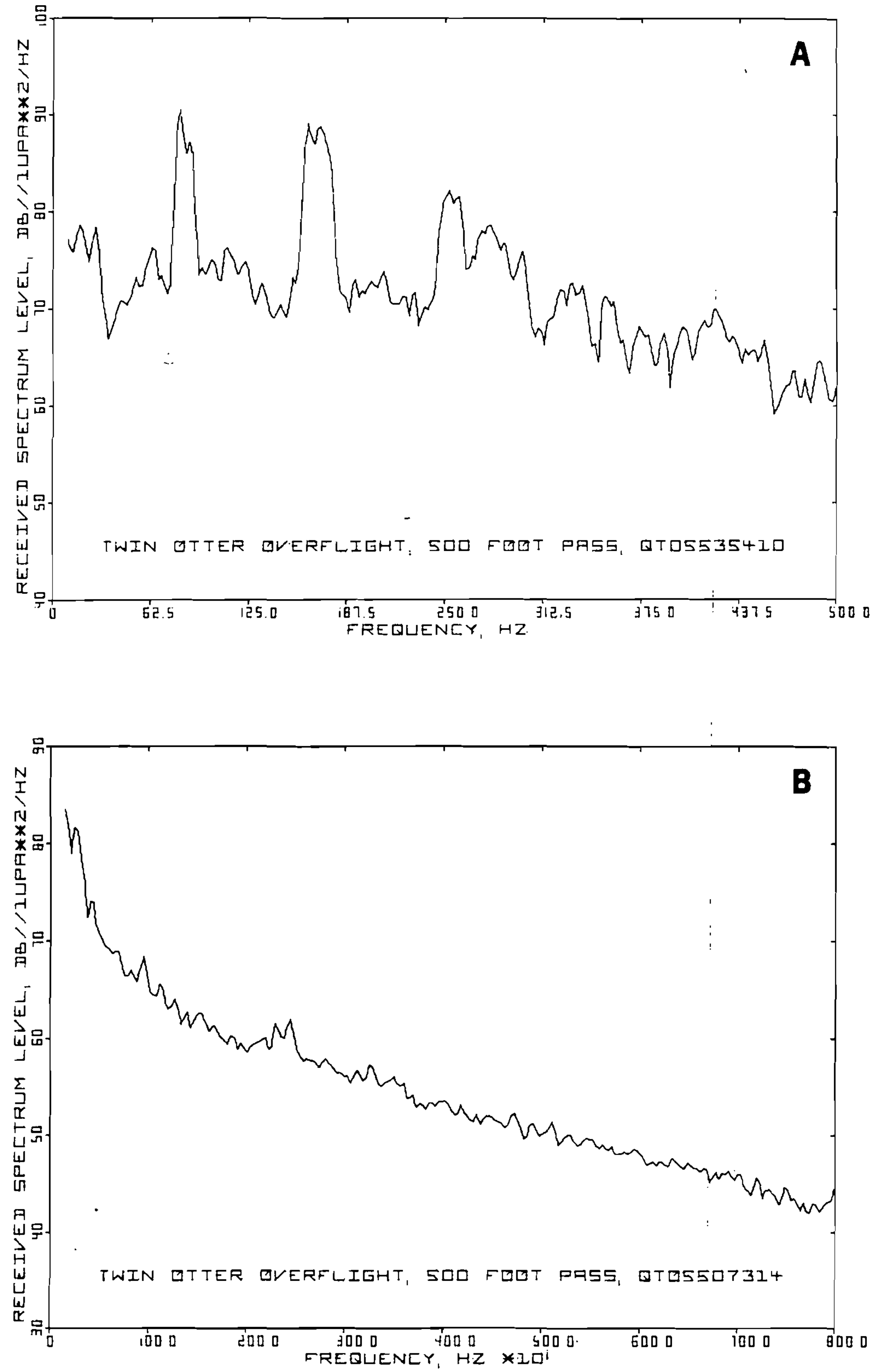


FIGURE 21. Averaged spectra for a Twin Otter aircraft flying at 500 ft (152 m) ASL over a hydrophone. **(A)** is for 10-500 Hz; averaging time 16 s. **(B)** is for 160-8000 Hz; averaging time 1 s.

and 2450 Hz may be turbine blade components. The levels of the tone around 82 Hz were measured during flyovers at four altitudes, averaging over the 4 s of strongest signal. The resulting levels were 104 and 110 dB// 1 µPa for two passes at 500 ft, and 112 dB for 1000 ft, 99 and 102 dB for 1500 ft, and 100 dB for 2000 ft. These levels are higher than those for the strongest tone from the Islander.

Analysis of the ambient noise measured just before the Twin Otter arrived reveals that in the 10-500 Hz band only a tone at 278 Hz (probably from the drillship 21 km distant) came close in level to the spectrum attributed to the Twin Otter in Figure 21A. Similarly, the ambient levels in the band from 160-8000 Hz were far below the levels in Figure 21B up to 7000 Hz.

Figure 22 contains spectrograms of the Twin Otter flyby at 500 ft. The three strongest tones in the spectrograms match the peaks in the averaged spectrum in Figure 21A. When I listened to the tapes, the aircraft noise was detectable for 33 and 36 s during two passes at 500 ft ASL, for 29 s during a pass at 1000 ft, and for 37 s during a pass at 1500 ft (seismic survey signals partially obscured the tapes from other passes).

Bell 212 Helicopter

The Bell 212 is a medium-sized two-engine turbine-powered helicopter commonly used in supporting offshore work. By special arrangement with Esso Resources Canada Ltd., one came to 'Sequel's' anchorage (at 70°02'N, 133°56'W, water depth 25 m) on 5 August 1981 for noise measurements. This location was about 2 km from that where the Twin Otter was recorded. The sea state was Beaufort 1. The H56 hydrophone was used, suspended at a depth of 9 m. The sky was clear and the wind speed was 5 knots.

The main rotor has two blades that turn at 324 rpm, we were told. The two-bladed tail rotor turns at 1650 rpm. The engine output shaft speed is 6600 rpm, the power turbine turns 33,000 rpm, and other turbines rotate at 39,000 rpm (H. Stuart, Bell Helicopters, pers. comm.). Flights over 'Sequel' were made at airspeeds within 5 knots of 100 knots with the main rotor rpm at 100%. If these rotation rates are correct, the main rotor blade fundamental

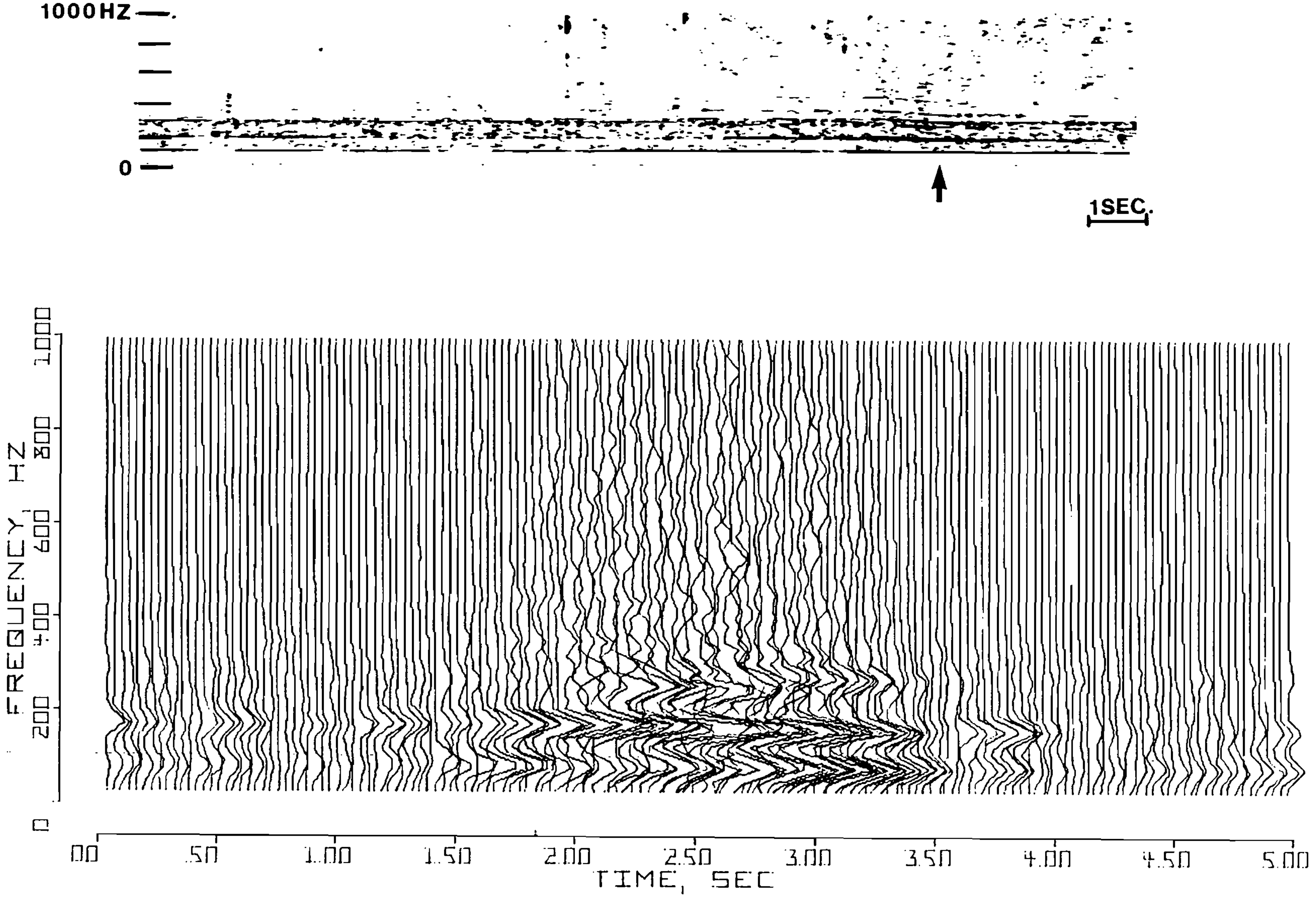


FIGURE 22. Spectrograms for a Twin Otter aircraft at 500 ft (152 m) ASL.

should appear at 10.8 Hz in the spectrum and the tail rotor blade rate should be 55 Hz.

Figure 23 contains averaged spectra for the helicopter flyby at 500 ft. In this case the averaging for the 10-500 Hz analysis was over only 4 s to minimize (1) Doppler shift effects and (2) inclusion of periods with low received levels. The strongest tone occurs at 20 Hz; the next tone is at 32 Hz. These peaks are probably related to the main rotor, but why the 10 Hz component is not evident is not clear.

A harmonic family with a fundamental at 112 Hz is evident in Figure 23. Other members have measured frequencies at spectral peaks of 224 and 334 Hz. These may be attributable to the tail rotor blade rate. Other tones appear at 54, 168, 280, 390, and 468 Hz.

Figure 24 contains spectrograms of the helicopter flyover at 500 ft. Accurate frequency measurement is difficult from these displays, but the dominant harmonic family has its fundamental slightly above 50 Hz.

Figure 24 shows that the helicopter sound was strong for only 2 or 3 s during a flyover at 500 ft. When I listened to the tapes via headphones, the helicopter was detectable for considerably longer, and the duration of audibility seemed to depend on its height: about 16 and 21 s during two passes at 500 ft, 18 and 27 s for passes at 1000 ft, and 26 s for a pass at 2000 ft. Corresponding values for the Twin Otter were somewhat higher (see above). Based on the helicopter's speed of about 100 knots (51.5 m/s), these figures imply that the helicopter would be audible to lateral distances from its flight path of about 500, 600 and 700 m, respectively. The data for both the Bell 212 and the Twin Otter were collected under low sea state conditions.

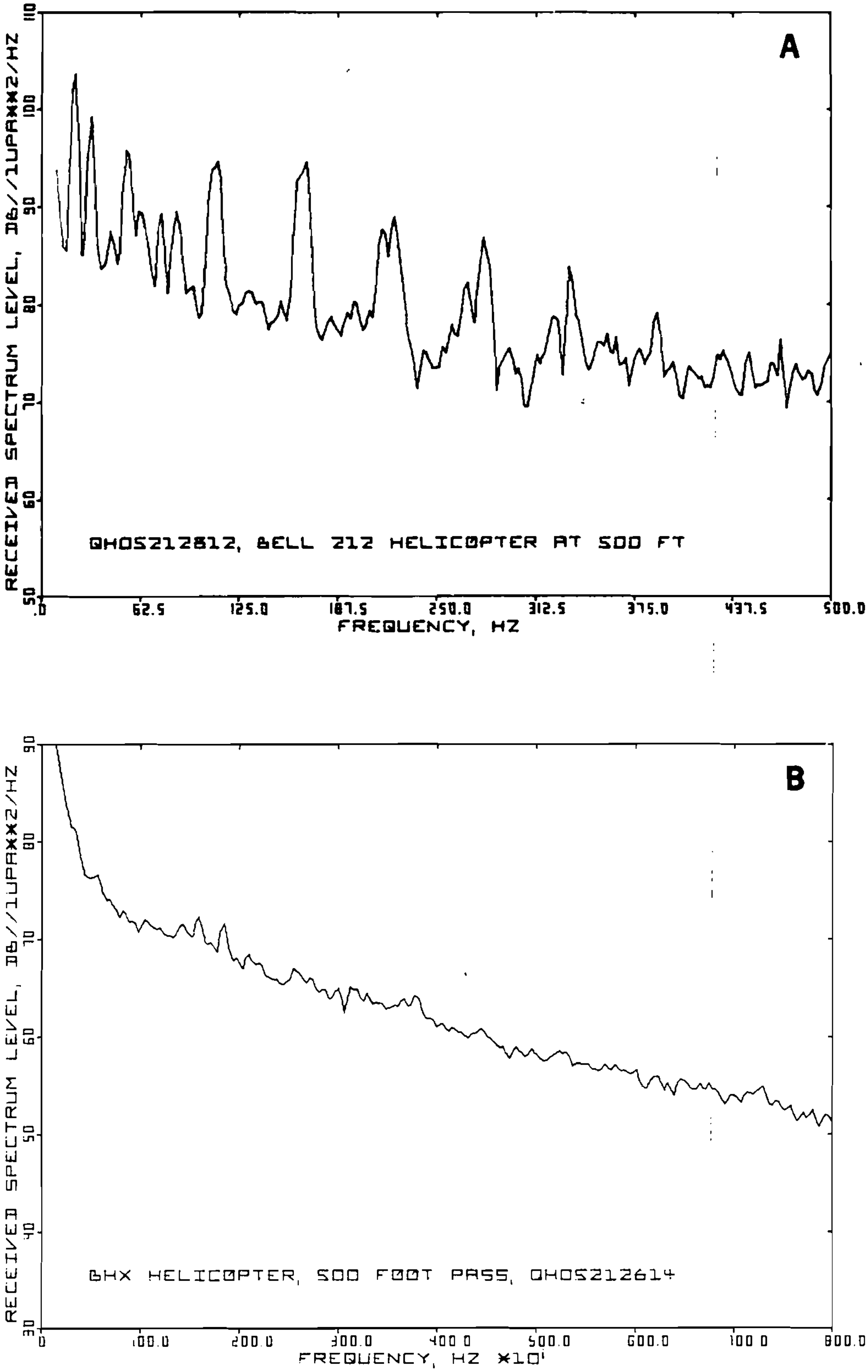


FIGURE 23. Averaged spectra for a Bell model 212 helicopter flying at 500 ft (152 m) ASL over a hydrophone. **(A)** is for 10-500 Hz; averaging time 4 s. **(B)** is for 160-8000 Hz; averaging time 1 s.

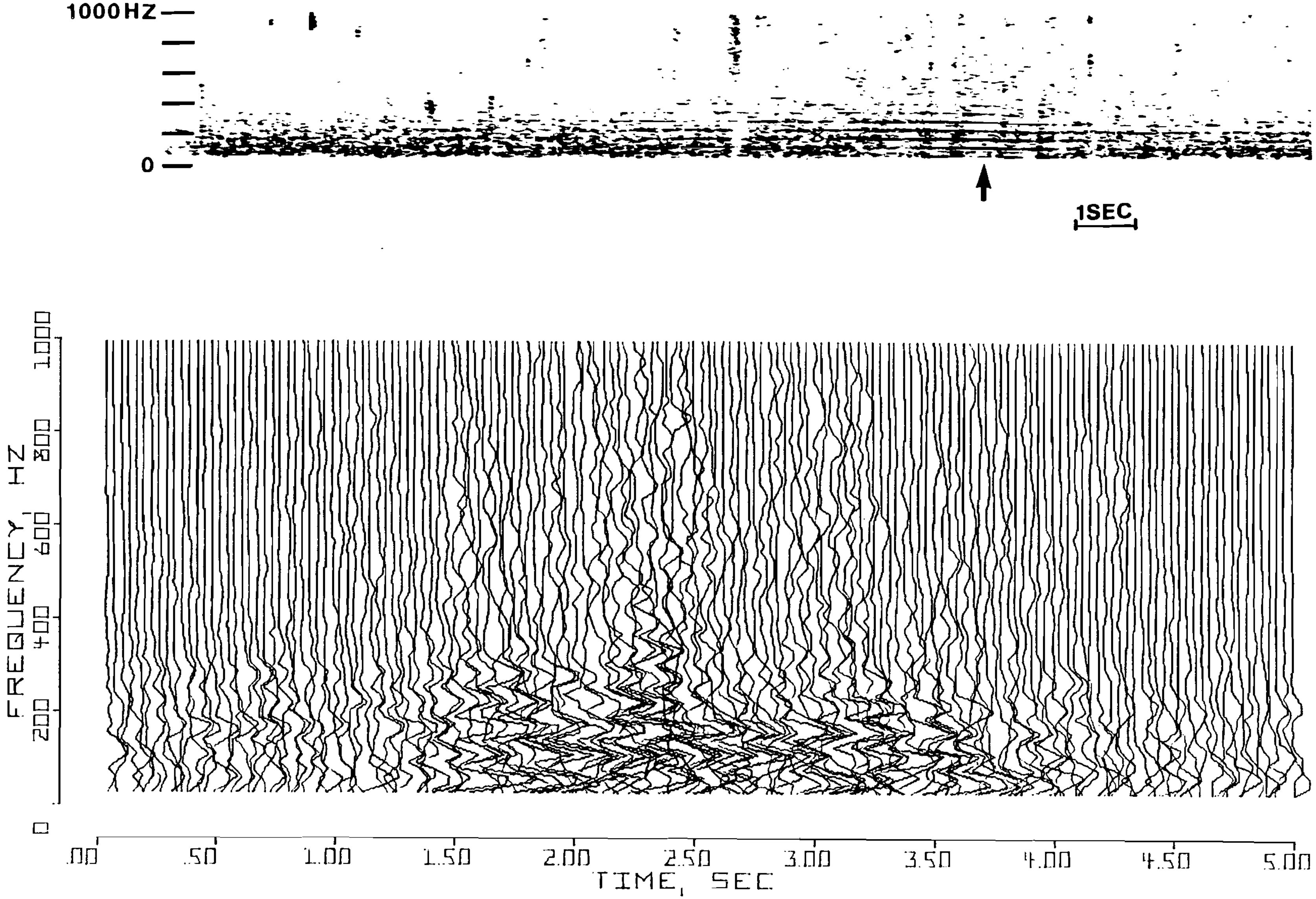


FIGURE 24. Spectrograms for a Bell 212 helicopter at 500 ft (152 m) ASL.

Comparison of Three Aircraft Types

Rigorous comparisons of the sounds received from the three aircraft is impossible because of differences in locations, water depth, sea state and (for the Islander vs. the other two) recording system. The strongest tones from the Twin Otter and Bell 212 helicopter had similar levels, and these were higher than the level of the strongest tone from the Islander (Table 3). However, a comparison of the broadband spectra of the three aircraft flying at 500 ft (Figs. 19B, 21B, and 23B) shows that the helicopter is clearly the strongest at frequencies both $\leq$1000 Hz and >1000 Hz.

Table 3. Levels of strongest tones vs. altitude for overflights by three aircraft types. All levels were taken from power spectra averaged over the 4 s of signal with maximum level.

	Freq. of strongest tone (Hz)	Altitude of Overflight			
		500 ft 152 m	1000 305	1500 457	2000 610
Twin Otter	82	110 104	112	99 102	100
Islander	70	102 100	96 95	93	97 96
Bell 212	20	109	107	?	101

The duration of audible aircraft sounds during flyovers by the Twin Otter and Bell 212 helicopter were determined by listening to the tapes with high quality playback equipment in a quiet environment. The aircraft were audible for 16-37 s, depending on type and altitude of the aircraft (see above). There was some indication that the Twin Otter was audible for longer than the Bell 212, but minor differences in recording location or sea state (Beaufort 0 for Twin Otter and Beaufort 1 for Bell 212) rather than aircraft type may have been the controlling factor.

Seismic Survey Signals

Signals from the seismic survey vessel 'Arctic Surveyor' were received at 'Sequel' numerous times during 1981 while we were recording background and industrial noises. The signal source consists of four sets of sleeve exploders, three sleeves per set, suspended over the side of 'Surveyor'. The geometry is a rectangle approximately 12 m long and 25 m wide (athwartship). The sleeves are deployed 6 m below the surface, water depth permitting. A mixture of propane and oxygen is exploded simultaneously in all the sleeves to produce a strong signal focused in the vertical direction. The signal echoes from bottom inhomogeneities are received at hydrophones in a long linear array deployed behind the ship. At each station, echoes from six 'pops' are recorded before moving 40 m to the next station along the survey track. Six to ten seconds elapse between pops while the exhaust gas is purged and the sleeves are recharged; 1/2-2 min elapse between series of 6 shots as the ship moves to the next station.

Except in the 8 km case, the position of 'Surveyor' was not known to 'Sequel' when the survey signals were recorded. However, as part of the seismic survey highly accurate positions of each shot point were obtained aboard 'Surveyor' using shore-based navigation stations operated by Canadian Engineering Surveys. The Esso Resources Canada, Ltd., personnel conducting the survey were very cooperative and provided us with positions of 'Surveyor' for specified dates and times corresponding to the reception of signals at 'Sequel'. Accurate positions of 'Sequel' were obtained from the on-board navigation satellite receiver/computer as well as from radar fixes of known installations such as Issungnak Island, 'Explorer II', and Alerk Island. Thus it was possible to compute the range between 'Sequel' and 'Surveyor' with confidence.

The ranges varied between 8 and 28.7 km. Three signals were analyzed from 8 km, three from 13 km, and six from ranges between 25.3 and 28.7 km. Examples of the signals are displayed in Fig. 25. Note that in each case the signal that begins at the sleeve exploders as an impulse is received as a kind of 'chirp' signal in which high frequencies are received first followed by a downward transition to lower frequencies. This shift is evident in Figure 25 as an increase in the period of the pressure oscillation from left to right. The received signal length is approximately 250 ms at 8 km and over 400 ms at 28.7 km, although the reverberation extends much longer. These properties of impulsive signal propagation are characteristic of the geometrical dispersion observed with signals undergoing multiple reflections between the surface and bottom.

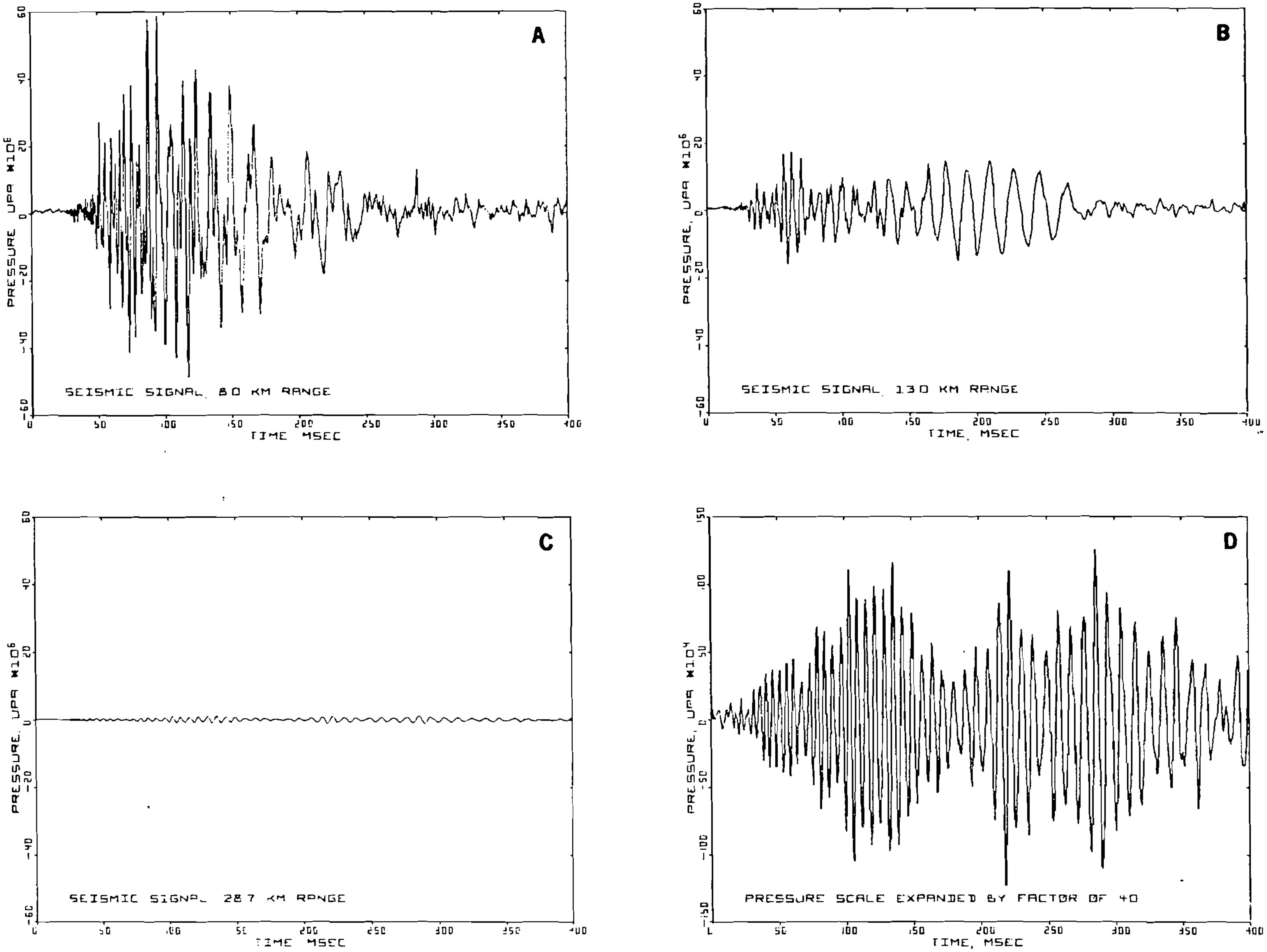


FIGURE 25. Seismic survey signals received from the sleeve exploders on 'Arctic Surveyor'. **(A)** 8 km. **(B)** 13 km. **(C)** 28.7 km. **(D)** Same as C but amplified 40 times.

Using the pressure-time plots of the twelve sample signals, the peak pressures were read and converted to dB with respect to 1 microPascal (rms). A regression fit of a simple spreading loss equation to these data resulted in the following equation:

$$\text{Received Level (dB//1 } \mu\text{Pa)} = 207.2 - 61.6*\log(R)$$

where R is in kilometres. This equation predicts values too low at 13 km and is probably not useful at ranges <8 km or >28 km, i.e. outside the range of the data. Furthermore, cylindrical spreading (expected in shallow water) is described by 10*log(R) and spherical spreading (expected in deep water) is described by 20*log(R). A 'spreading loss' term of 61.6*log(R) seems unrealistic.

The result of a regression fit of an equation containing both R and log(R) terms to the data resulted in the following:

$$\text{Received Level (db//1 } \mu\text{Pa)} = 170.2 - 1.385*R - 10.12*\log(R).$$

This equation is intuitively realistic because the spreading loss term is very close to the cylindrical spreading--10*log(R)--expected for shallow water. Figure 26 is a graph of the data and this equation. An equation like the earlier one would result in a straight line on this graph, and clearly would not fit the data very well.

Another equation was derived with the coefficient of log(R) forced to be 10, in effect forcing a cylindrical spreading loss term. The result was

$$\text{Received Level (dB//1 } \mu\text{Pa)} = 170.1 - 1.39*R - 10*\log(R).$$

The standard error was 2.2 dB and the coefficent of determination was 0.972.

What is the range over which the equation is useful? At some range less than 8 km the spreading loss can be expected to be greater than 10*log(R). Perhaps more important, the geometrical dispersion which changes the shape and spectral distribution of the signal will make the equation invalid at short ranges. Clearly, the peak pressure of the impulse near the sleeve

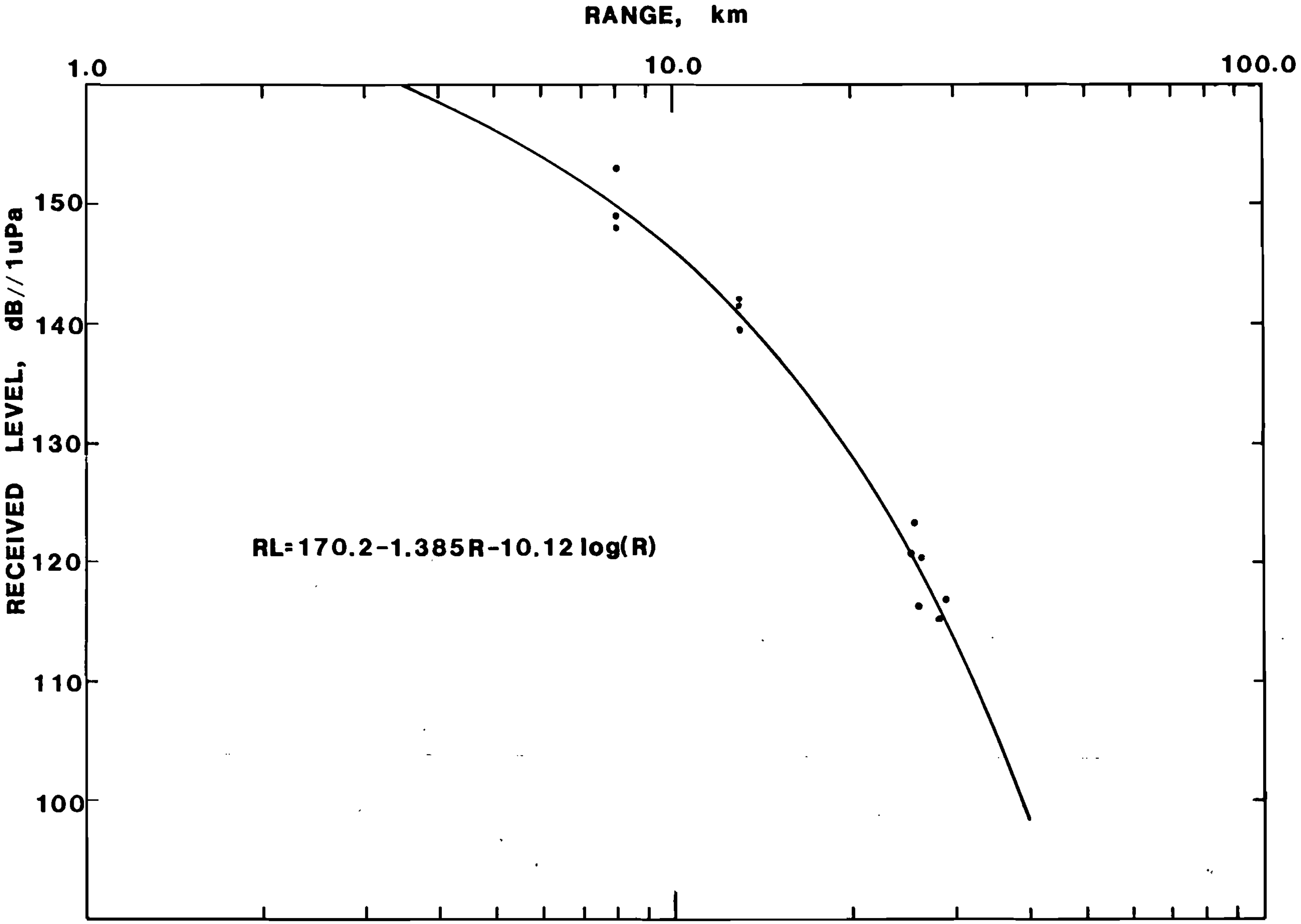


FIGURE 26. Received levels of seismic signals vs. range. The best-fitting regression model is also shown.

exploders will not be predicted by this equation. Thus, this equation should not be used to predict received levels at ranges much below 5 km.

Other constraints of applicability are imposed by the source depth (6 m), the receiver depth (9 m), the water depth (ranging from about 15 to 30 m), and the signal frequency (generally between 120 and 180 Hz). Changes in any of these parameters may be expected to result in different received levels for any given range.

Another useful result may be extracted from the signal at 28.7 km portrayed in Figure 25. The range of frequencies seen, as determined by the signal periods in the graph, extends from about 100 to 200 Hz. Considering that the original impulsive signal contained a far broader spectrum of energy, one can conclude that sound propagation in these shallow waters of the eastern Beaufort Sea favors signals in the 100-200 Hz range. The frequencies of many bowhead whale calls occur in this same range (Ljungblad et al. 1982; Würsig et al. 1982).

A seismic survey signal of unknown origin was recorded on 'Sequel' at 70°09'N, 134°29'W at 10:36 MDT on 6 August (water depth 34.5 m). Neither the 'Arctic Surveyor' nor the 'Arctic Sounder' were conducting surveys at the time. The time signature of the signal is presented in Figure 27 because it has a different character than the sleeve exploder signals presented in Figure 25. Other seismic signals of unknown origin are shown in Figure 14.

Also presented in Figure 27 is the time signature of the single 40 in^3 (655 cm^3) airgun signal received at a sonobuoy located about 5 km away. This signal was recorded on 18 August 1981 in about 25 m of water at 70°03'N, 134°46'W during a disturbance trial (Fraker et al. 1982). The same down-shift in frequency with time (increasing periods) that has been seen in every impulsive signal is manifest. The signal caused overload distortion in the sonobuoy system so the amplitude measurements are not reliable. As recorded, the amplitude corresponds to 123 dB//1 μPa, or 33 dB less than the 'Surveyor' signals would be expected to be at 5 km. Put another way, the airgun signals at 5 km appear to be equivalent to the sleeve exploder signals received at 24 km. However, the 'Surveyor' signals received at 25 to 28 km range with reliable instrumentation are not so strong as to cause the

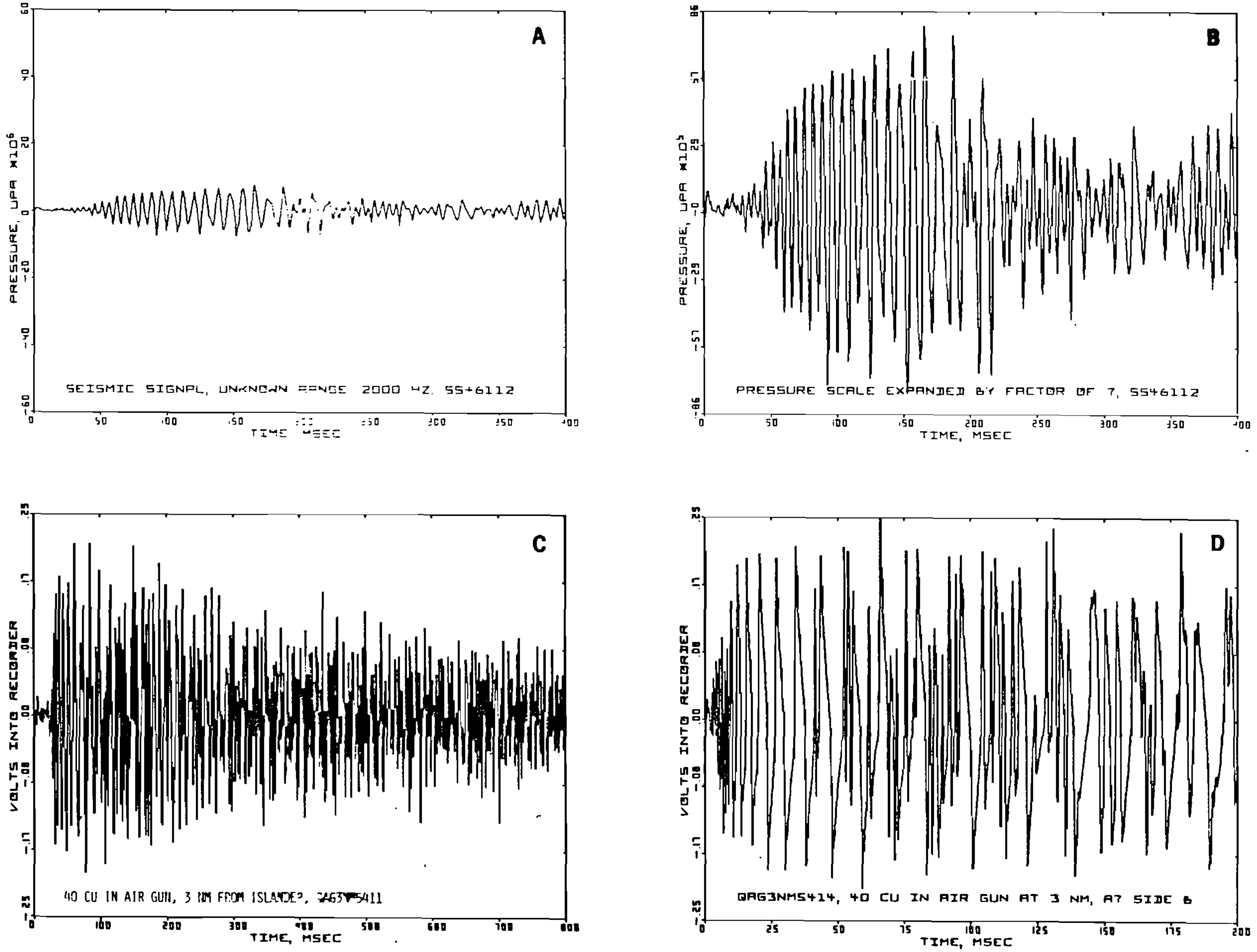


FIGURE 27. An unknown seismic survey signal received at 'Sequel' (A and B). A typical signal from the 40 cu in airgun used in the disturbance trial at 5 km is shown in C and D.

sonobuoys to overload. Thus, it appears that the signals from the airgun at 5 km were stronger than 123 dB//1 µPa, but the actual level is unknown.

The recorded amplitudes from the airgun at 3 km correspond to 118 dB//1 µPa, or 5 dB less than the recorded amplitude of the airgun signal from 5 km. However, the measurement technique of simply observing the strong portion of the received signal does not appear applicable to signals from less than 5 km. At such short ranges, the number of multipath arrivals is insufficient to form fully the dispersed signal (the downward frequency chirp) characteristic of impulsive signals from longer ranges.

Note that the sonobuoy used to record the airgun signals is more sensitive at increasing frequencies, so the time signature displayed in Figure 27 is not strictly comparable to the signatures in Figure 25, which came from the flat-response system used on 'Sequel'.

Drillship Noise--'Explorer II'

We hoped to be able to record waterborne sounds near a drilling operation on an artificial island. Such recordings have been obtained in the Alaskan Beaufort Sea in winter (Malme and Mlawski 1979), but not during the open water season when conditions for sound propagation are different. Unfortunately, drilling was not underway on any of the islands in the eastern Beaufort Sea during our field periods in either 1980 or 1981. However, four drillships were operating in the area in both years, and we recorded their sounds. Results from 1980 were confounded by the activities of supply boats near the drillship, so only the 1981 results are discussed below.

During August 1981, the Dome/Canmar drillship 'Explorer II' was operating at North Issungnak (70°05'33"N; 134°26'42"W) for Gulf Canada Resources, Ltd. The drilling engineers had been informed of our requirements and were available for queries on VHF radio. On the evening of 5 August, 'Sequel' maneuvered within the mooring lines and anchored at a distance of 0.1 n.mi. (185 m) off the port quarter. The water depth was 27 m. Canmar 'Supplier III' was moored alongside 'Explorer II'. With a hydrophone at a depth of 9 m, we recorded drillship sounds for an hour that evening, during which time the operating conditions changed frequently. The drill bit was at a depth of 2031 m on 6 August.

The drillship equipment included her main engines and two mud pumps. The main engines were Caterpillar diesels, model 399, which are 12-cylinder, four-cycle engines usually operated at 1000 to 1500 rpm. Normally, five of these engines are running. The mud pumps each contain three pistons and operate at 55 strokes/minute. The drill string rotates at speeds up to 120 rpm. The mud pump frequency is too low to detect but the rotation rate of the string can be heard as a beat frequency. Evidently it modulates the other sounds radiated by the drillship.

At greater drill depths, an 800 rpm turbine is used at the drill bit. Conceivably the turbine noise could propagate up through the bottom and into the water, but we have no data on this noise source.

The 'bang rate' of the main diesels would be expected to dominate the radiated noise spectrum from the drillship. Using the description above, the fundamental frequency should occur in the range from 100 to 150 Hz. However, it was generally found to be higher. On the evening of 5 August the fundamental changed from 210 Hz to 200 Hz to 184 Hz to 136 Hz. The changes occurred in steps clearly audible on the monitor headphones. Weaker tones were found at frequencies between 360 and 1528 Hz; only once was there a harmonic relationship. The 1528 Hz tone varied only to 1520 Hz, indicating that its source was not mechanically linked to the fundamental tone.

On the morning of 6 August the fundamental tone had increased to 278 Hz. Data were again recorded from the 0.1 n.mi. anchorage, followed by recordings from 0.2, 0.5, 1.0, 2.0, and 4.0 n.mi. (i.e. from 0.185 to 7.4 km). The strongest tone varied from 278 to 274 Hz, indicating a fairly stable operation during the 2 h that elapsed while the signals were recorded. However, a secondary tone occurred at 254 Hz, suggesting that perhaps not all the prime power plants were being operated at the same speed. The presence, and frequency, of higher frequency tones varied from station to station; particularly strong tones occurred at 560, 1528, and 1640 Hz, but not at every station.

Figure 28 contains graphs of the measured spectrum of drillship 'Explorer II' at 0.1 n.mi. (185 m). The tones attributed to the prime power

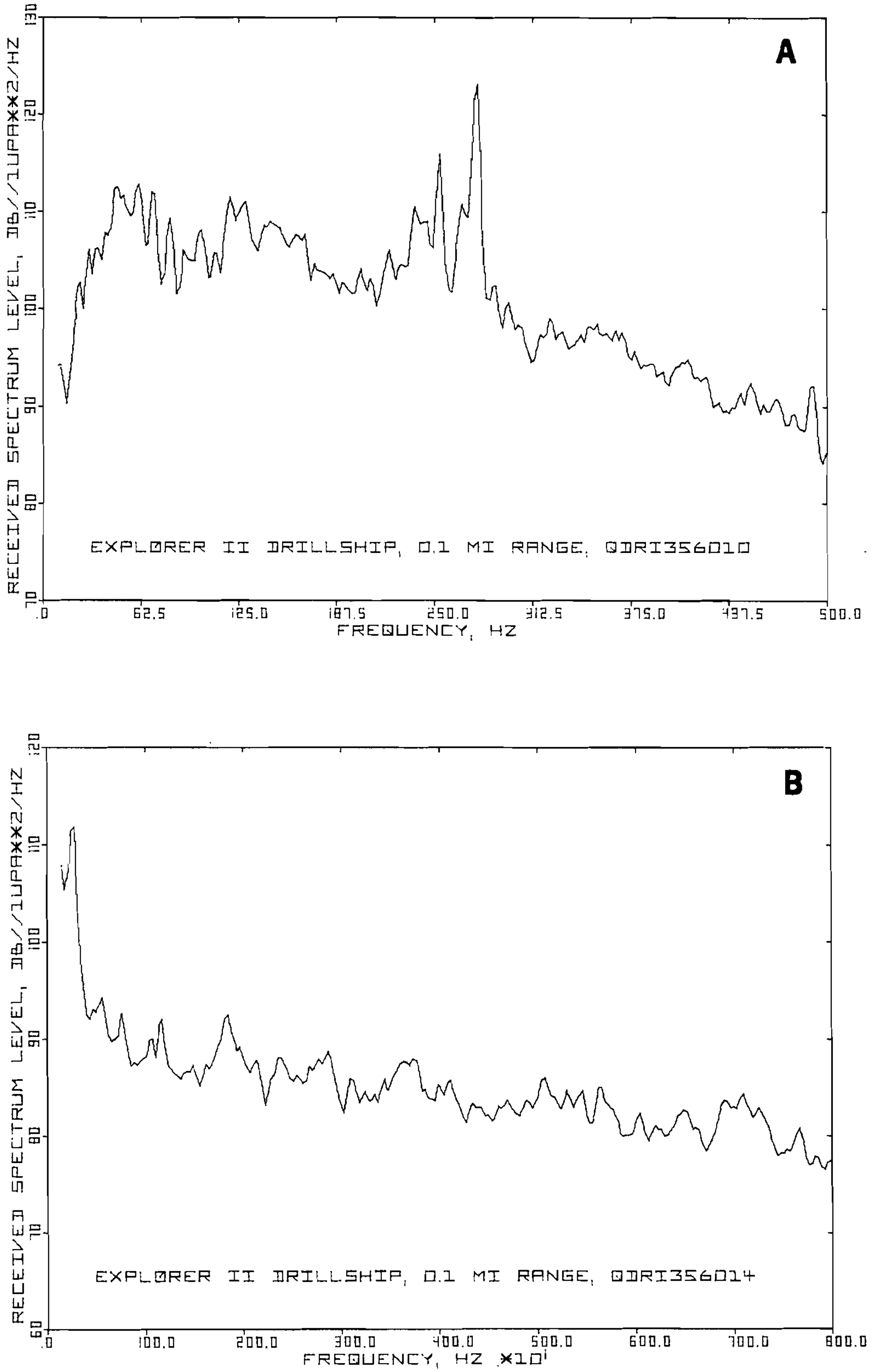


FIGURE 28. Averaged spectra at 0.1 n.mi. (185 m) for the drillship 'Explorer II'. **(A)** is for low frequencies (10-500 Hz); averaging time 16 s. **(B)** is for a broad range of frequencies (160-8000 Hz); averaging time 1 s.

plants may be seen readily at 278 and 254 Hz. This figure provides the best characterization of the noise spectrum from the drillship. Spectrograms of the drillship at 0.1 n.mi. are presented in Figure 29. The averaged spectra shown in Figure 28 came from this segment of data. The broad, intense and continuous quality of the tone at 278 Hz shows clearly.

Figure 30 contains two pairs of graphs of measured spectra from the drillship, all recorded at 0.1 n.mi. Each pair covers one operating condition with separate graphs for the low- and wideband frequency ranges as in Figure 28. In one condition the ship operation resulted in a tone at 210 Hz; in the other, the tonal frequency was 136 Hz. In this case, the reduction in speed resulted in a reduction in the radiated power as well.

Figure 31 is a graph of the received level for the 278 Hz tone at the five ranges at which data were recorded (0.1 to 4.0 n.mi., or 185 to 7413 m) and the equation adopted as a realistic fit to those received levels. A regression analysis of the levels resulted in the following equation:

$$\text{RL (dB//1 } \mu\text{Pa)} = 123.1 - 1.58{*}R - 9.7{*}\log(R)$$

where R is in kilometres and the logarithm is to the base 10. In the shallow waters in which the data were recorded, one would expect cylindrical spreading, or a 10*log(R) term. Because the calculated and theoretical values (9.7 and 10) are so close, and because a similar analysis of signal levels from seismic surveys provides a calculated value (10.12) even closer to that expected from cylindrical spreading (see above), the regression was repeated with 10*log(R) forced into the equation. The result was

$$\text{RL (dB//1 } \mu\text{Pa)} = 122.9 - 1.52{*}R - 10{*}\log(R).$$

This is the equation plotted in Figure 31. The constant term depends upon the source level and transmission losses out to the range at which the data began, or about 185 m. The second term is an absorption term and accounts for an exponential loss in received power with increasing range. In a ray model of sound propagation, such a loss could be attributed to a 'bounce loss' equivalent to 1.52 dB per kilometre. Acoustic rays reflected from the bottom lose energy into the bottom and surface reflections result in

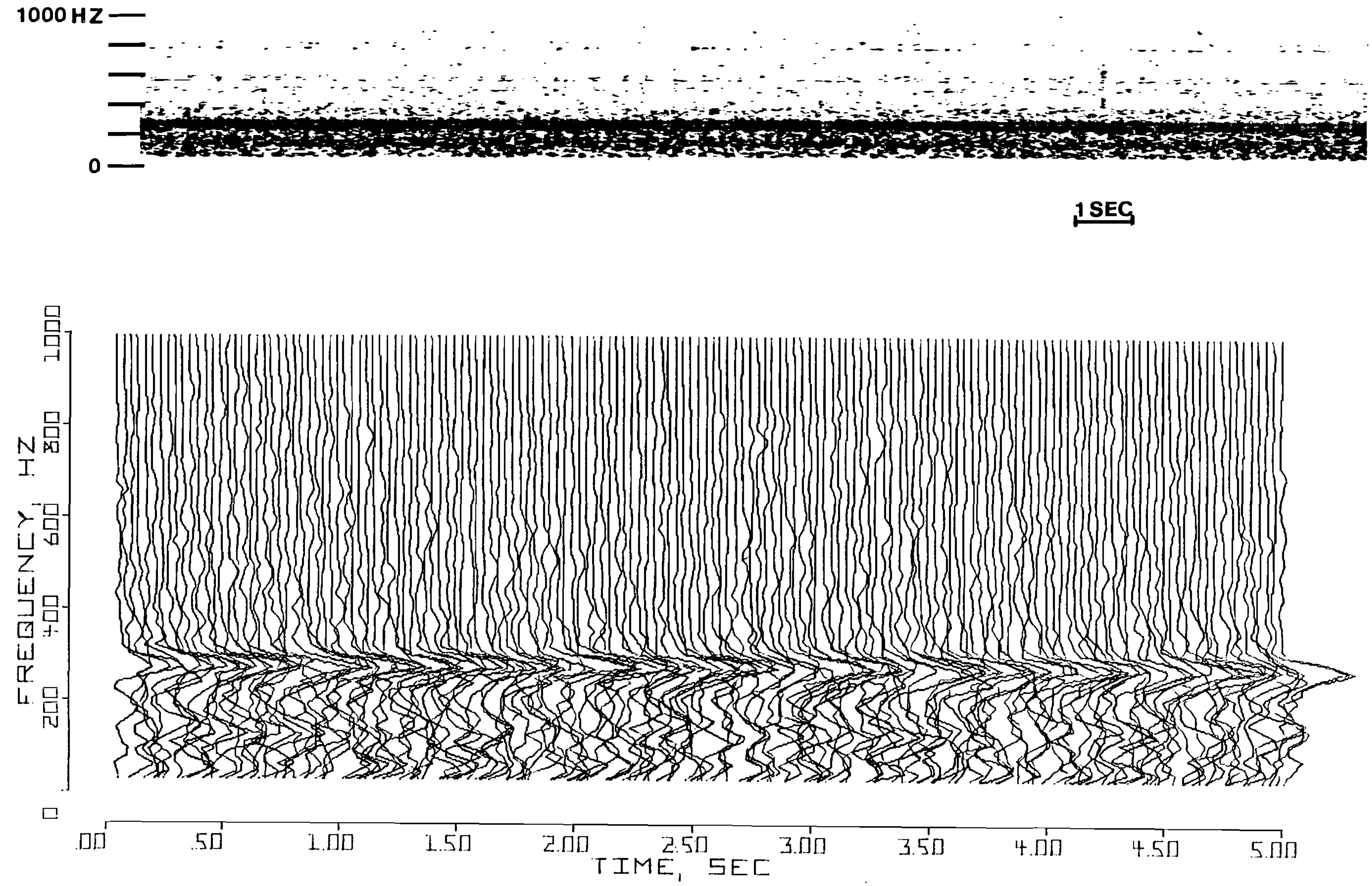


FIGURE 29. Spectrograms at 0.1 n.mi. (185 m) for the drillship 'Explorer II'.

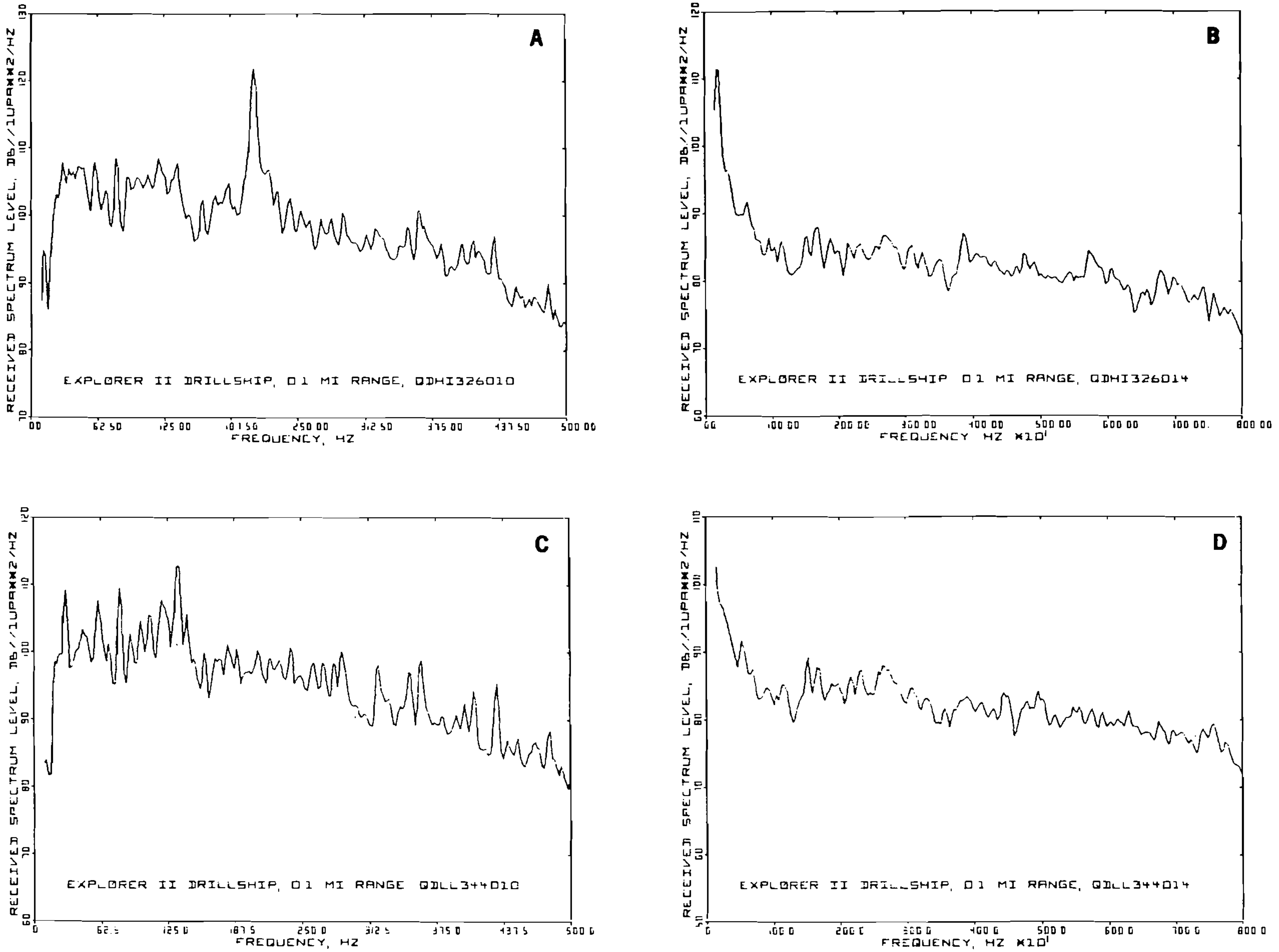


FIGURE 30. Averaged spectra at 0.1 n.mi. (185 m) for two other operating conditions of the drillship. Parts 'A' and 'B' show a strong tone at 209 Hz; parts 'C' and 'D' show a strong tone at 135 Hz.

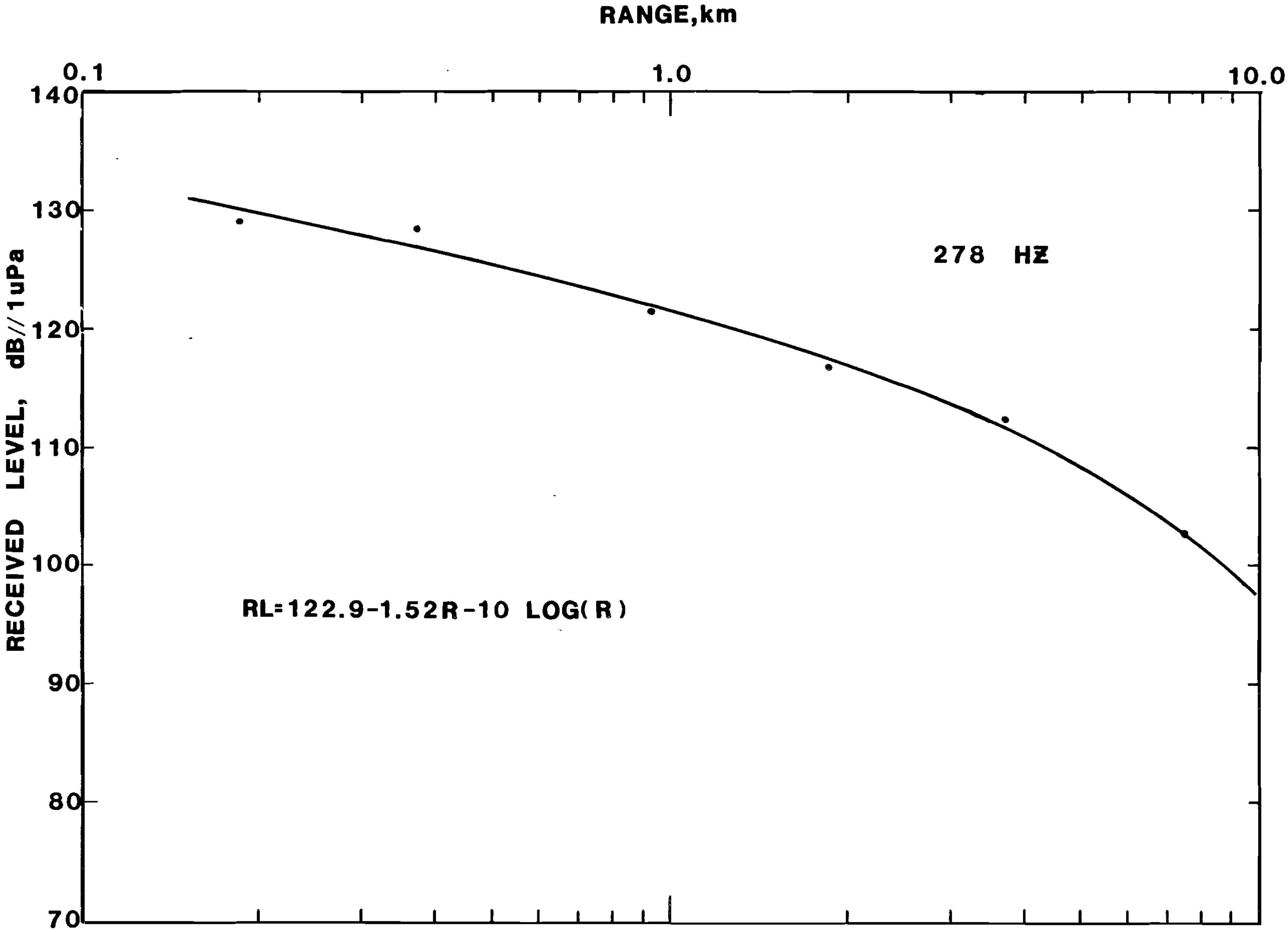


FIGURE 31. Received signal level vs. range for the 278 Hz tone from the drillship. The dots show the measured data and the line was filled by a 'least square error' technique (see text).

scattering losses. This term is expected to be frequency dependent because higher frequencies lose more power per bounce than do lower frequencies. However, the equation is probably realistic over frequencies from 100 to 300 Hz. Note that for a range of 100 m the received level is predicted to be 132.7 dB.

The close fit of the equation ($R^2 = 0.95$, $n = 6$) to all points indicates that the equation is applicable across the range within which the data were collected, or from 0.185 to 7.4 km, and predictions of received signal levels to twice that range, or 15 km, would probably be realistic. Comparison with the similar equation for the received level from seismic survey signals (see above) suggests that the present equation is valid to at least 30 km.

For comparison, the received levels of the 254 Hz tone were also analyzed. The more general regression resulted in the following equation:

$$\mathrm{RL}\ (\mathrm{dB}//1\ \mu\mathrm{Pa}) = 115.8 - 2.01*R - 8.3*\log(R).$$

The regression with a forced cylindrical spreading term was

$$\mathrm{RL}\ (\mathrm{dB}//1\ \mu\mathrm{Pa}) = 115.1 - 1.70*R - 10*\log(R).$$

It would be interesting to compare these results with those of Buerkle (1975) who studied the semi-submersible 'Sedco J' in water 63 m deep in the Bay of Fundy. However, he used one-third octave bands for analysis and it is not clear whether the high levels in some of those bands are from tonals or continuous components of noise. His peak in the 16 Hz band is probably tonal, but we have seen no significantly high levels at that frequency from 'Explorer II'. He found spectrum levels of 117 $\mathrm{dB}//(1\ \mu\mathrm{Pa})^2/\mathrm{Hz}$ at 100 m in the 125 Hz band and 115 dB in the 200 Hz band with a drop to 112 dB in the 160 Hz band in between. The dominant tonal from 'Explorer II' sometimes occurred in this frequency range. If the 115 dB spectrum level in the 200 Hz band is in fact the result of a tonal in that band, then its sound pressure level is 131.3 dB//1 μPa at 100 m. This is essentially the same as the 132.7 dB predicted for the dominant tonal from 'Explorer II' at 100 m.

Dredge Noise

Dredge 'Beaver Mackenzie' at Issungnak Island, 1980

Recordings of dredge and other noises were made at Issungnak Island shortly after midnight on 7 August 1980. The operating log for the dredge 'Beaver Mackenzie' recorded 'pumping' during the hours of the test. The suction dredge 'Beaver Mackenzie' is an 86.5 m vessel with a gross tonnage of about 2200. The suction and discharge pipes are 0.85 m in diameter. The dredge is equipped with three pumps ranging in power from 1500 to 1700 hp. The dredged material is transported through a floating pipeline to the discharge point. When underway, the 'Beaver Mackenzie' is propelled by two 975 hp diesels that turn two variable-pitch, two-bladed propellers.

The sailing vessel 'Ungaluk' approached the dredge from the north, an H56 hydrophone was deployed using a 6-m sparbuoy for suspension to isolate the sensor from wave motion, and recordings were made on board. The hydrophone depth was 13 m; the water depth was 18 m. Pushed by wind, the 'Ungaluk' drifted away from the dredge during the recording session. An Arctic Transport Ltd. tug was maneuvering near 'Ungaluk' until the hydrophone was deployed; the tug then moved away toward the dredge. A sketch of the relative locations of the dredge, 'Ungaluk', artificial island, and 'Arctic Breaker' (a barge serving as a camp for the work crews) is presented in Figure 32. The radar on the 'Ungaluk' was inoperative and it was necessary to judge distances by eye. The time-of-day was within 2 h of local midnight, but the weather was clear and there was adequate daylight. We estimated the initial range from the dredge to be about 1200 m.

Figure 33A-C presents received spectrum levels for this range. The overall broadband level is strong, on the order of 90 dB at 100 Hz, but only two tonal components appear below 500 Hz. The strongest tone, relative to the broadband levels at nearby frequencies, occurs at 1776 Hz.

Figure 33C,D compares the received levels for higher frequencies at ranges of about 1200 and 4600 m. The overall decrease in level between these two distances is conspicuous. However, even at 4600 m levels were consistently higher than under quiet conditions (Figs. 33D vs 5B).

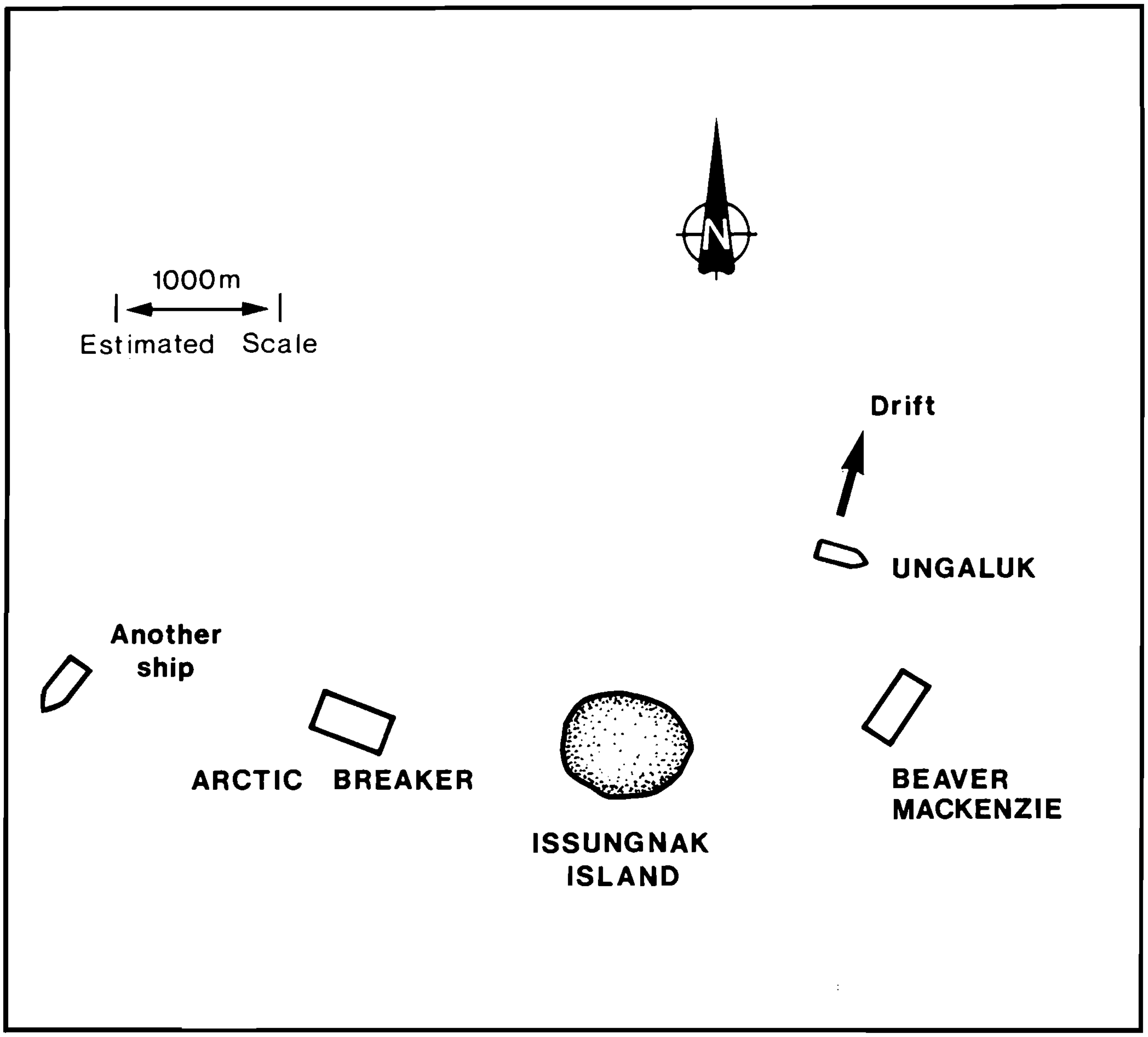


FIGURE 32. Relative positions of the dredge 'Beaver Mackenzie' and various vessels during the period of sound recording at Issungnak Island, 7 August 1980. Island and vessels not drawn to scale.

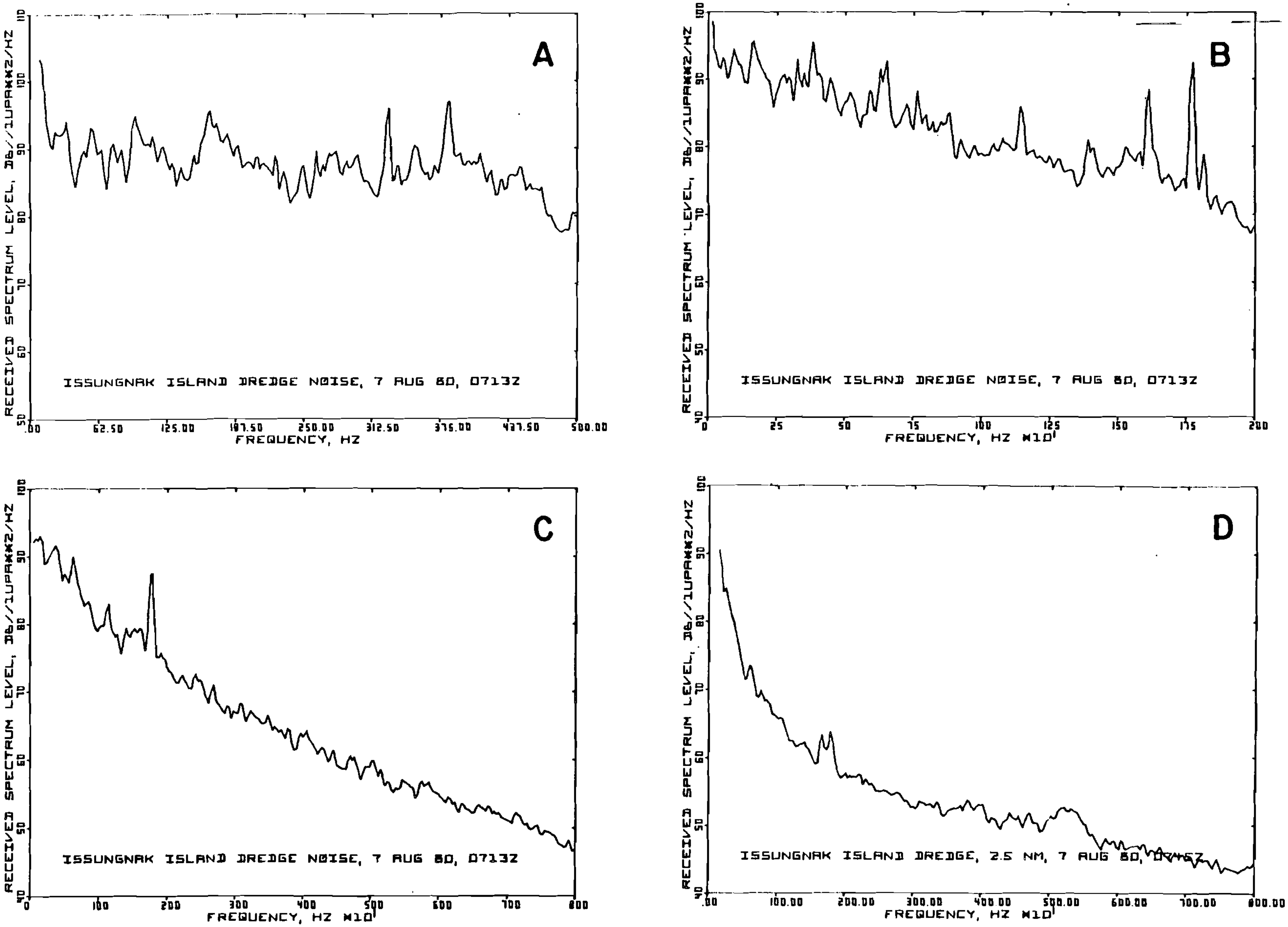


FIGURE 33. Averaged spectra for the construction operation at Issungnak Island, 7 August 1980. **A-C.** Recordings at a distance of about 1200 m from the dredge considering frequencies 10-500 Hz, 40-2000 Hz and 160-8000 Hz, respectively. Averaging times 16, 4 and 1 s. **D.** Recording at a distance of about 4600 m, 160-8000 Hz; averaging time 1 s.

Dredge 'Beaver Mackenzie' at Alerk Island, 1981

The dredge 'Beaver Mackenzie' was within a few days of completing construction of the artificial island at Alerk late on the evening of 6 August 1981 when 'Sequel' approached to make recordings. As with the drillship, the operators had been informed of our intentions and the smaller support vessels in the vicinity remained clear as we maneuvered among the mooring lines. A rough sketch of the relative locations of the dredge, 'Sequel', and the island is presented in Figure 34. The water depth was 13 m at the first recording station 0.1 n.mi. (185 m) from the dredge and increased only to 15 m at the final station 4.0 n.mi. (7.4 km) distant. The hydrophone depth was nominally 9 m but a strong current may have served to lift the hydrophone to a shallower depth.

Figure 35 contains spectra computed for dredge signals received from 0.1 n.mi. (185 m). The tonal components were not particularly stable in amplitude. The peak at 1590-1670 Hz was especially variable. The peak at 374 Hz appeared at other frequencies at the other recording stations; the highest frequency observed for this component was 384 Hz. Not showing in the figure are tonal components at 656 and 844 Hz, which were evident on a 20-1000 Hz analysis (Fig. 36). Neither of these tones was present at the next recording range (0.24 n.mi., or 440 m) but at that site there was a tone at 592 Hz.

The two spectrograms displayed in Figure 36 provide an indication of the fluctuations in the tonal components of the dredge signal. The spectra in Figure 35 are averaged over 4 s (10-500 Hz) and 1 s (160-8000 Hz) from the data displayed in Figure 36.

Figure 37 contains spectra for the dredge signals recorded at 4.0 n.mi. (7.4 km). Levels were well above quiet ambient conditions. The marked null at 64 Hz probably results from frequency-selective effects associated with bottom characteristics. We have observed a similar effect in sound propagation in the Bering Sea. The strong peak at 100 Hz recorded at 0.1 n.mi. (Fig. 35) has either been adversely influenced by this null, or the source of that particular tone on the dredge had changed between the two recording periods, or both.

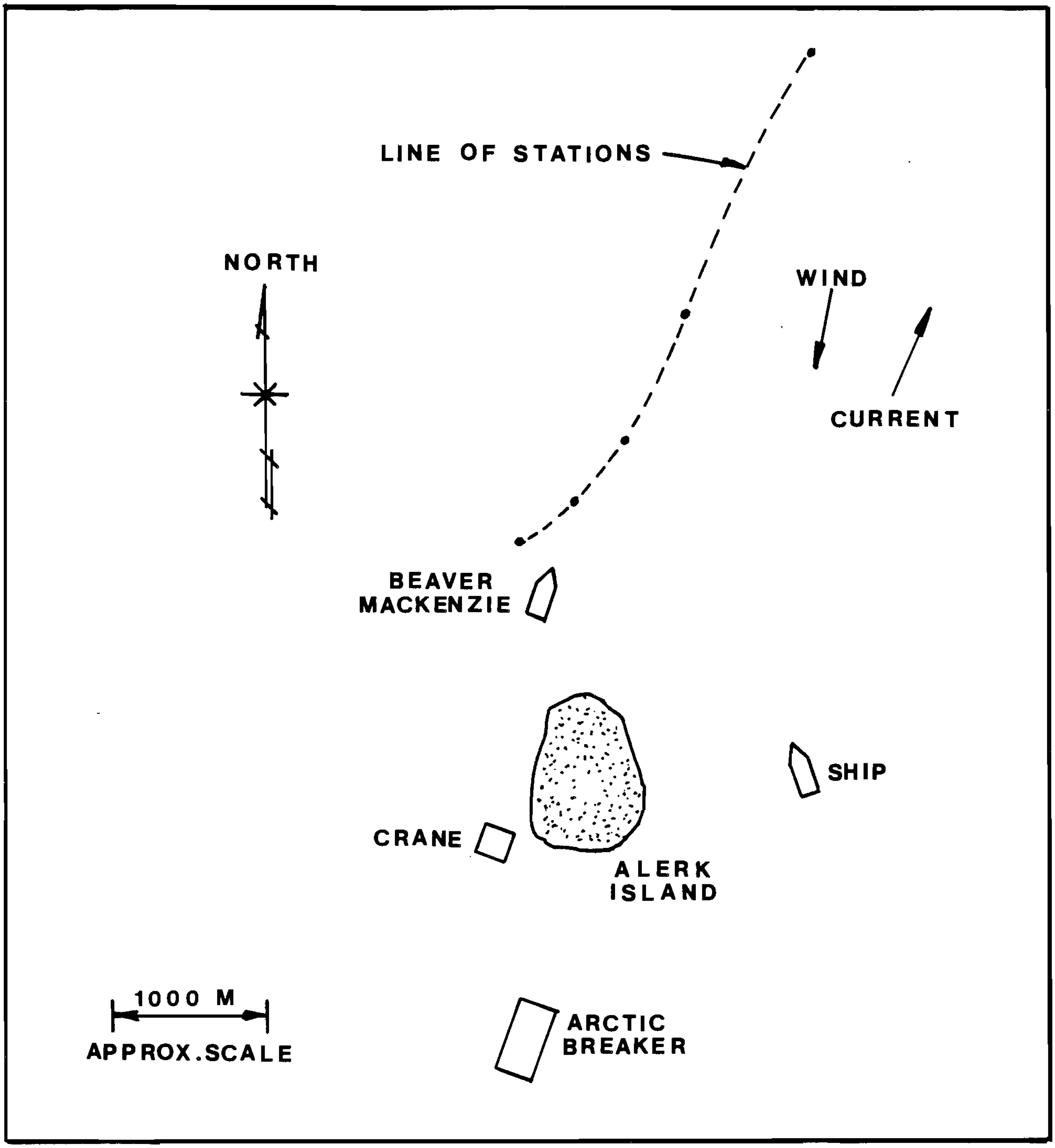


FIGURE 34. The relative positions of the artificial island at Alerk, the dredge 'Beaver Mackenzie', the measurement locations, and other vessels, 6 August 1981.

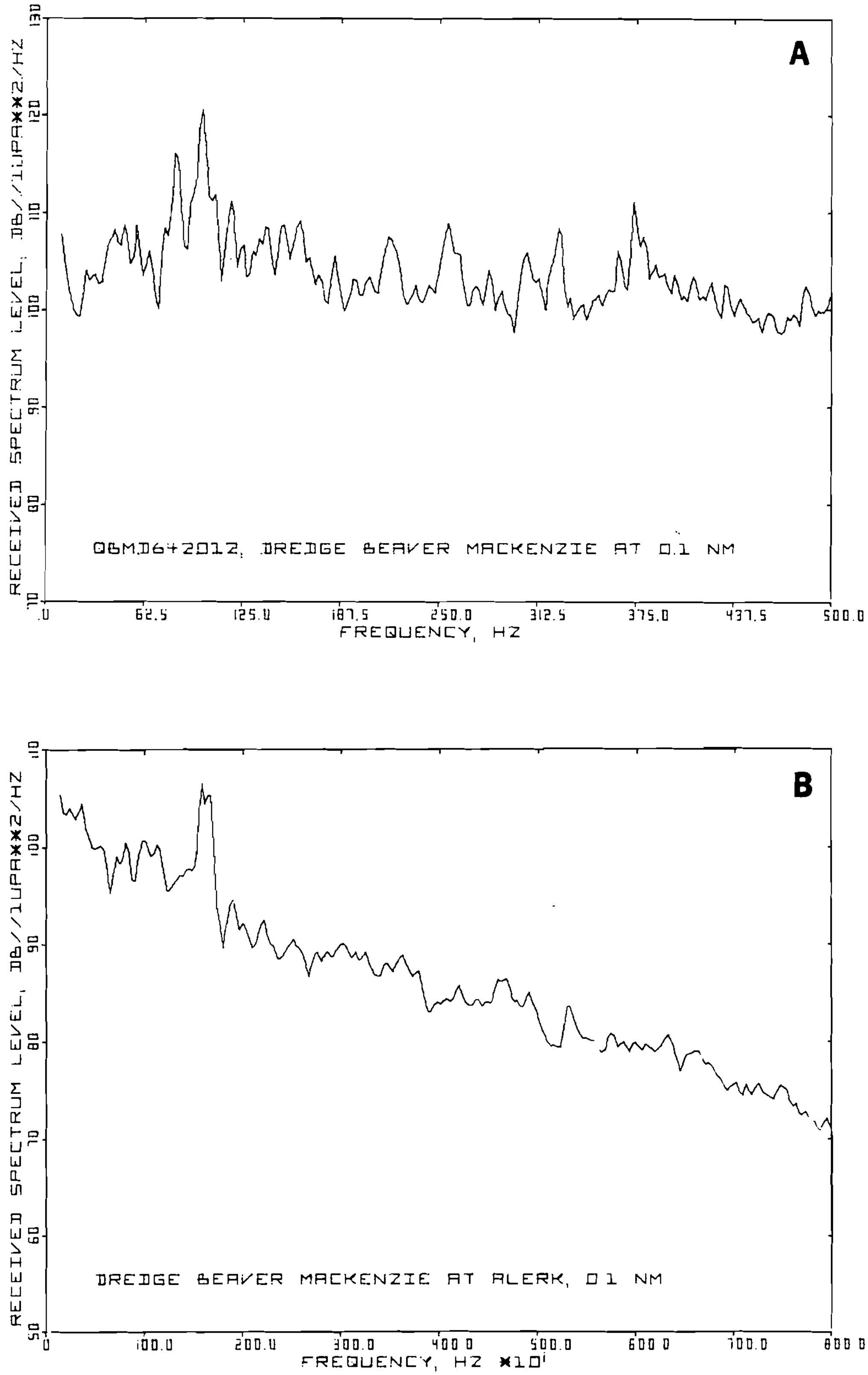


FIGURE 35. Averaged spectra at 0.1 n.mi. (185 m) from the dredge 'Beaver Mackenzie' during the final phase of construction of an artificial island at Alerk. **(A)** is for 10-500 Hz; averaging time 4 s. **(B)** is for 160-8000 Hz; averaging time 1 s.

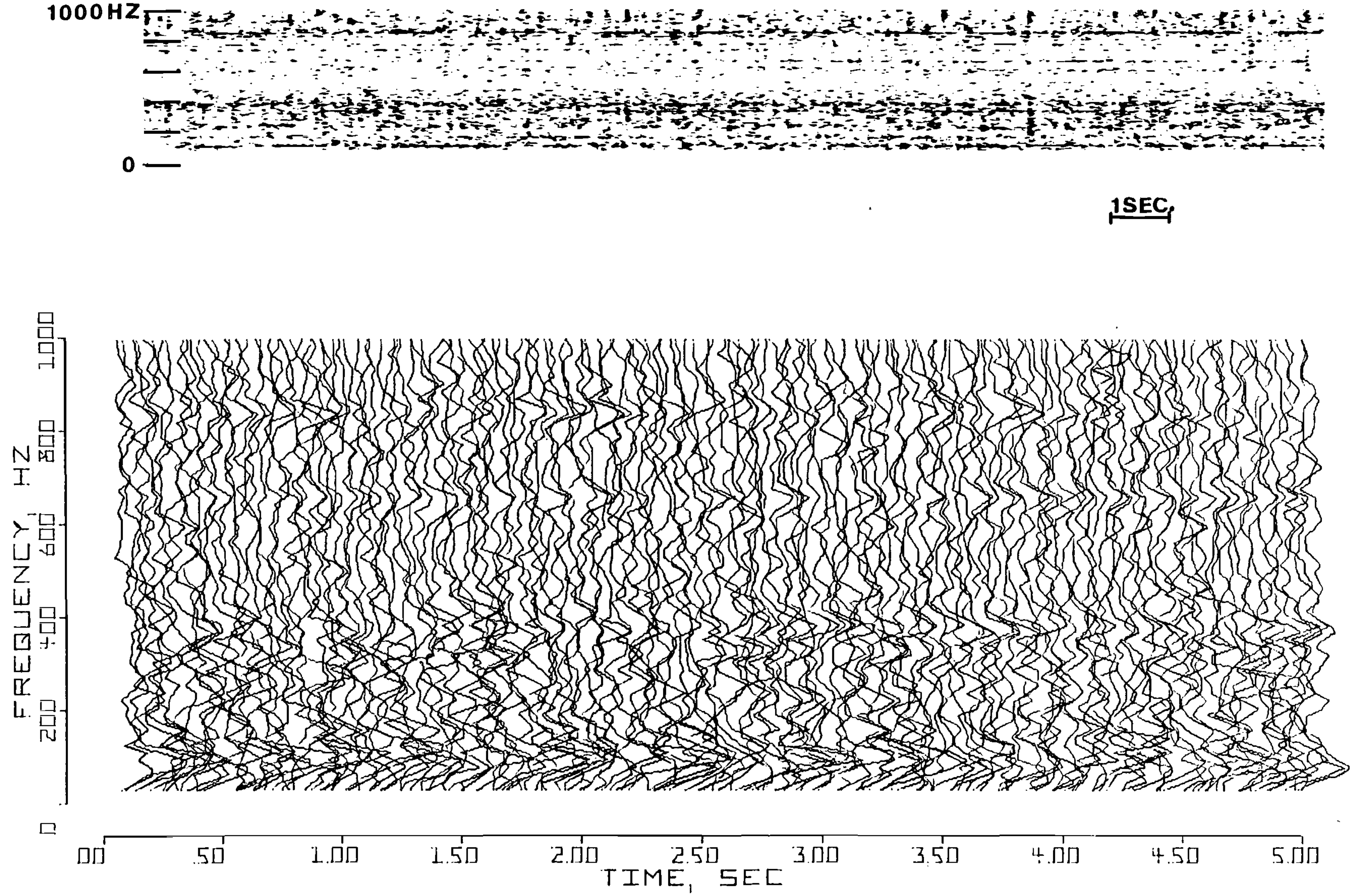


FIGURE 36. Spectrograms for the dredge 'Beaver Mackenzie' at 0.1 n.mi. (185 m).

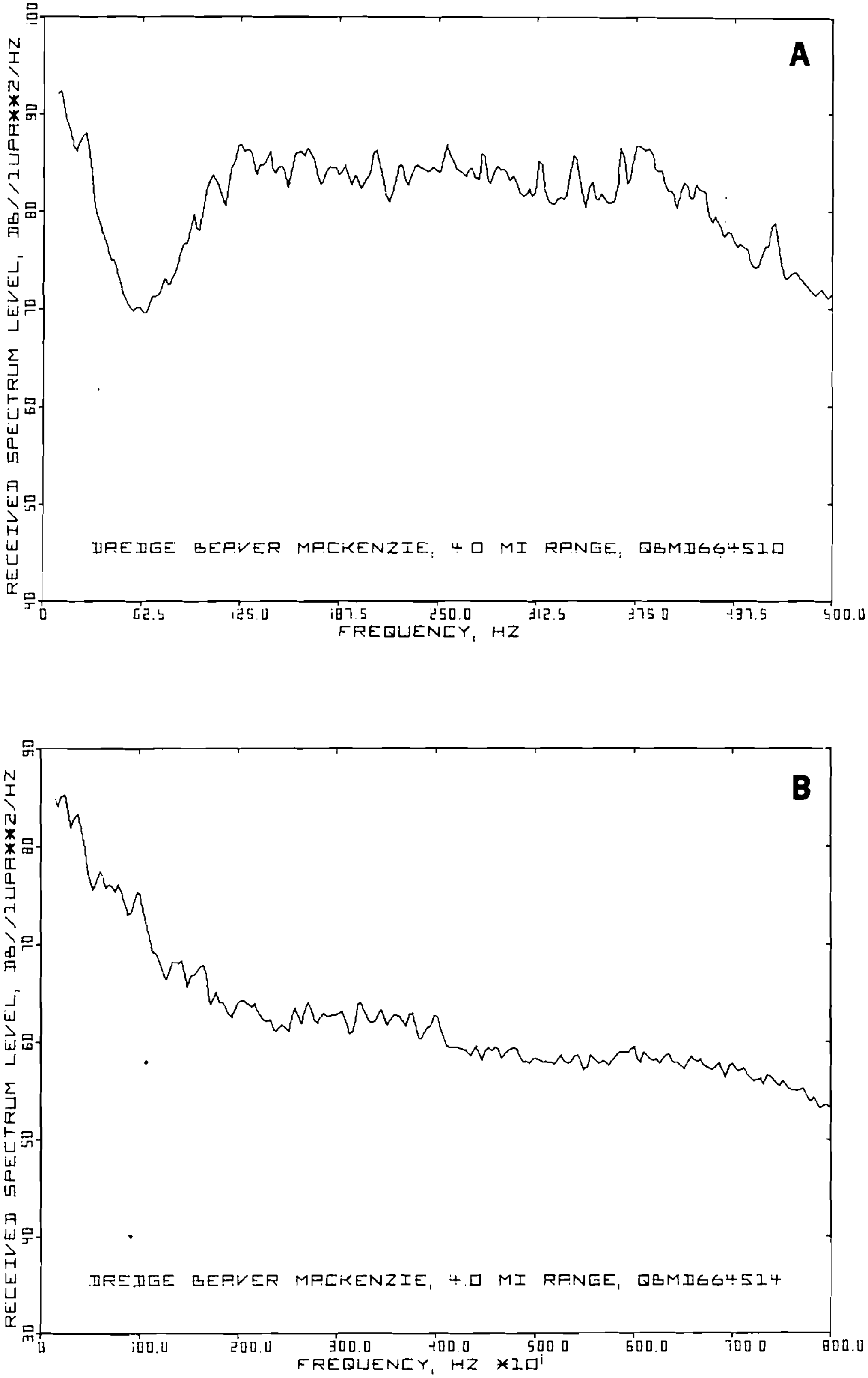


FIGURE 37. Measured spectra of the dredge 'Beaver Mackenzie' at 4.0 n.mi. (7.4 km).

The best dredge signals for studying sound propagation were the 380 and 326 Hz tones. For the 380 Hz tone, which was stronger, a least square error fit to six measured received levels at 0.185 to 7.4 km resulted in the equation

$$RL\ (dB//1\ \mu Pa) = 109.4 - 0.770*R - 11.9*\log(R).$$

The range R is in kilometres. The standard error was 3.89 dB and the coefficient of determination was 0.899. When cylindrical spreading was postulated by forcing a 10*log(R) term, the resulting equation was

$$RL\ (dB//1\ \mu Pa) = 110.0 - 1.13*R - 10*\log(R).$$

The standard error was 3.41 dB and the coefficient of determination was 0.512 (n = 6).

For the 326 Hz tones, the equation resulting from the general regression model was

$$RL\ (dB//1\ \mu Pa) = 106.7 - 0.789*R - 9.43*\log(R).$$

The standard error was 1.32 dB and the coefficient of determination was 0.982. Forcing a 10*log(R) term resulted in

$$RL\ (dB//1\ \mu Pa) = 106.5 - 0.680*R - 10*\log(R).$$

The standard error was 1.16 dB and the coefficient of determination was 0.766.

Considering the apparent variability in the source, these results are encouragingly consistent with the equations derived for the other in-water industrial noise sources studied during the project. A comparison is made in the next section.

Sound Transmission Loss

A summary of the equations for received level for four noise sources studied in detail is shown in Table 4. Also included in that table are estimates of the levels that would be received 100 m from the sources.

The constant term in each equation is influenced by the type of source for the particular frequency involved, and by the transmission loss between the source and the range at which cylindrical spreading can be said to begin. For the longer ranges considered here, the range at which cylindrical spreading begins is not important; cylindrical spreading can be assumed to apply across all distances considered. The constant terms and estimates for 100 m provide rough indications of the relative source levels of the various source types. However, actual source levels referred to 1 m cannot be estimated reliably from these equations, and even the estimates for 100 m are questionable because cylindrical spreading has been assumed but may not apply.

The coefficient of the R term is important because it indicates how signal attenuation varies with frequency. The largest value (2.53 dB/km) occurs for the highest frequency considered (1000 Hz) and the smallest value (0.17 dB/km) occurs for the lowest frequency (about 80 Hz). An increase with frequency is expected because this term corresponds to an 'absorption loss' term and results from absorption in the water and in the bottom as well as from scattering at the sea surface. As the spreading loss term (in dB) is proportional to log R and corresponds to a loss in pressure amplitude proportional to an inverse power of R, so the absorption loss (in dB) is proportional to R and corresponds to a loss in pressure amplitude proportional to an exponential function of R. Qualitatively, for a given sound ray path bouncing between the bottom and the surface, one can conceive of a given loss 'per bounce'. This will be equivalent to some loss 'per unit distance' or loss per kilometre. At the surface, the frequency effect occurs because, for low frequencies, the surface is effectively smooth and the sound is not scattered; while for high frequencies the presence of waves or a broken ice cover causes the surface to appear rough and the sound energy to be scattered on reflection. At the bottom, the properties of the sedimentary material may be more absorptive for higher frequencies.

Table 4. Equations for received level from four noise sources studied in the eastern Beaufort Sea in 1981. Cylindrical spreading is assumed.

Source					
Type	Frequency (Hz)	Water Depth (m)	Constant*	Linear Term*	Estimated Level at 100 m**
Seismic	c.150	various shallow	170.1	-1.39	c.180
Drillship	278	27	122.9	-1.52	133
"	253	27	115.1	-1.70	125
Dredge	380	13-15	110.0	-1.13	120
"	325	13-15	106.5	-0.68	117
'Geopotes X'	c.80	25	136.3	-0.17	146
	1000	25	119.5	-2.53	130

* Each equation is of the form

Received level (dB//1 µPa) = Constant + (Linear Term) R - 10 log R

where R is in kilometres and the logarithm is to the base 10.

** Estimated levels for 100 m range in dB//1 µPa and are based on the fitted equations. The value for seismic survey signals is a very general estimate because the equation was derived from measurements at much longer ranges and because of the special mode of propagation of seismic survey signals (see text).

It would be desirable to use the available data to determine an equation for the frequency dependence of sound transmission loss in the eastern Beaufort Sea. However, present data were collected at various places and times and with various types of sound sources. Thus, the 'fit' would be poor or difficult to substantiate with the limited data available. Additional measurements, preferably with a controlled source and at selected frequencies, would be invaluable. Such measurements could also provide valuable information on transmission loss between the source and 100 to 200 m range, beyond which cylindrical spreading appears to occur. The latter data are necessary before source levels referenced to the conventional 1 m distance could be calculated. Careful planning would be critical to success because peripheral parameters such as source type and water depth should be controlled to avoid confounding the results.

DISCUSSION

During the 1980 summer season we obtained quantitatively useful data from sonobuoys concerning noise from the Islander aircraft, the crew boat 'Imperial Adgo', the dredge 'Beaver Mackenzie', and bowhead whale calls. We also obtained less useful data, recorded from 'Ungaluk' without benefit of range measurements, of the same dredge and of drillship 'Explorer I', along with the boat 'Canmar Supplier VIII'.

During the 1981 summer season we collected more sonobuoy data and many more data from our boat system, including radar ranges and accurate position fixes from a Navigation Satellite receiver/computer. We determined received levels vs. range for sounds from a drillship ('Explorer II'), a dredge ('Beaver Mackenzie'), a ship ('Geopotes X'), and sleeve exploder seismic survey signals. In addition, we examined sounds from two more boats, a single airgun, and flyover sounds from a Bell 212 helicopter and a Twin Otter fixed-wing aircraft at different altitudes between 500 and 2000 ft. In cases of sounds recorded from the same source in both 1980 and 1981, as with the dredge, the results from the two years were consistent. We also recorded considerably more sounds from bowhead whales in 1981 than in 1980 (cf. Würsig et al. 1982).

From the 1981 data we have been able to characterize the qualities of various different sources of potentially disturbing sounds, and to develop equations to predict received levels from four of these sources for specified ranges. We have shown that cylindrical spreading plus an absorption term provides a useful model of sound transmission loss for the shallow water areas that were studied.

We have formulated a description of seismic survey signals for longer ranges (greater than about 5 km) in terms of the effective pressure received at a given range. This is in contrast to signal energy formulation that would be more conventional but would include the time dimension (the duration of the sound burst) as well as the pressure. It seems preferable to retain the two dimensions separately, as we have done, rather than to combine them in a single measure of energy.

It is common in underwater acoustics to describe a source of sound by its 'source level', which is a sound pressure level or pressure spectrum level referred to unit distance (usually 1 m). To be useful, one must know the transmission loss between unit distance and the range of interest. However, it is usually impossible to measure the source level directly at unit distance. Measurements at unit distance are useful only if the source can be treated as a single point. The sources of most of the sounds that we have studied are large. One cannot measure directly the source level of a large vessel, a dredge, or an array of seismic signal sources. The concept of source level becomes even more abstract in the case of an airborne source, such as aircraft.

Although there are problems with the concept of 'source level', it is in practice very desirable to have a standardized measurement of sound level at a constant distance that is sufficiently short that variations in propagation losses are not a factor. With source level known, one can predict received level for any ocean situation desired, for arbitrary water depth and sound speed structure, as long as the transmission loss characteristics are known.

In this report we have taken the view that an equation for predicting the received level of a specified sound for a specified range (e.g., 100 m to 10 km) will be more useful than trying to derive a source level *per se*. We realize that this has the effect of including the sound transmission qualities of the eastern Beaufort Sea, or at least of the area and time in which we made the recordings, in our description of the sound sources. If one wishes to determine what the received levels would be, in relation to range, in some other ocean or at some other time, then the equations for the eastern Beaufort Sea in August 1981 would not be applicable. However, one could use our results as a starting point. In addition, we have the assurance that the received levels used to derive the equations came directly from measurements and not through any assumed, and perhaps erroneous, model of sound propagation for the range from 1 m to 100 or 200 m.

The generality of our equations could be improved by obtaining measurements of short-distance sound propagation within our study area. This should be done using an accurately controlled point source (such as an underwater projector), and measurements should be taken out to a distance of at least a few hundred metres. Such data would allow calculation of theoretical source levels for the source types that we have already studied. These data would also provide a basis for modifying our equations so they can be used over a wider range of distances, and in other areas with different propagation conditions.

The different sources of noise that we studied can be compared within our formulation inasmuch as we have used the same measurement and descriptive techniques for most sound types. Thus, if a given sound source is known to cause a disturbance and another source does not, then a comparison of our measured spectra and levels for the two may help to determine why one source disturbs and another does not. It may also be possible to examine spectra from other sources to predict whether they are likely to disturb the animals.

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Ory Gorgichuk and John Chop of Esso Resources helped considerably by providing a tour of 'Arctic Surveyor', an explanation of how they conduct seismic surveys and how the equipment works, and trips to the archives to determine exactly where 'Surveyor' had been at specified times. Esso also provided the Bell 212 helicopter whose sounds were recorded.

John Ward of Dome Petroleum provided descriptive information on the 'Canmar Supplier' vessels and 'Geopotes X'.

Alfred Habermeyer, drilling engineer with Gulf Canada, provided information from drillship 'Explorer II' and a description of her equipment.

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Christopher Clark of Rockefeller University prepared the Spectral Dynamics spectrograms to serve as a link between the waterfall diagrams of this report and the spectrograms of bowhead sounds in the 'Normal Behavior' report.

Mark Fraker and John Richardson of LGL provided the guidance and leadership essential to the achievement of useful results. They have earned my gratitude and respect for their contributions to this work. Beverley Griffen and Helen Hogarth (LGL Ltd.) typed the report.

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CHARACTERISTICS OF BOWHEAD FEEDING AREAS*

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ABSTRACT

Physical and biological characteristics of areas where bowhead whales feed in the southeastern Beaufort Sea were studied during August and early September in both 1980 and 1981. **Physical measurements** from both years revealed two distinct water layers in the nearshore shallow water region where bowheads were feeding during August--(1) a warm and brackish surface layer, generally at depths 0 to 7.5-15 m, and (2) a colder and more saline layer below. Within the general feeding area, no differences were evident in either year between the temperature and salinity profiles in locations where bowheads were and were not observed. Waters in the general study area appeared to be a few parts per thousand (ppt) less saline in 1981 than in 1980. Vertical **zooplankton** hauls taken off Richards Island, N.W.T., and King Point, Y.T., in 1980 showed that hydrozoans and copepods were the dominant groups in terms of biomass (range for total biomass: 1302-12 mg/m^3 wet wt). Horizontal zooplankton tows taken off Tuktoyaktuk and Richards Island in 1981 also showed that copepods and hydrozoans were the dominant groups, in terms of biomass, with a minor contribution from amphipods (range for total biomass: 2456-0.06 mg/m^3 wet wt). Highest biomasses typically occurred below the thermocline (10 m and deeper) and usually were found just above the bottom. In both 1980 and 1981, five species of hydrozoans (*Halitholus cirratus*, *Euphysa flammea*, *Sarsia princeps*, *Aglantha digitale*, *Aeginopsis laurentii*) and five species of copepods (*Calanus hyperboreus*, *C. glacialis*, *Limnocalanus macrurus*, *Pseudocalanus minutus*, *Derjuginia tolli*) accounted for most of the biomass. However, the copepods contain much more energy per gram of wet weight. Drop net samples of **epibenthos** collected from two stations at King Pt., Y.T., in 1980 and at Station N-4 in 1981 suggest that mysids (*Mysis litoralis*), isopods (*Saduria entomon*) and to a lesser extent copepods and hydrozoans comprised almost all the biomass on or near the bottom (1980: 1313-424 mg/m^2 wet wt.; 1981: 350 mg/m^2 wet wt.).

The results from both 1980 and 1981 suggest that bowhead whales tend to occur at locations with a significantly higher biomass of copepods than present in surrounding areas. In 1981, when bowheads were observed feeding at or near the surface, horizontal tows showed copepod biomass near the surface to be an order of magnitude greater in those areas than where whales were not observed.

The average zooplankton biomass found in areas where bowheads were observed was 0.558 g/m^3 wet weight in 1980 and 0.449 g/m^3 wet weight in 1981. If bowheads are to consume their estimated daily caloric requirement each day, they must feed on aggregations of zooplankton that contain a somewhat larger average biomass than was found in either 1980 or 1981. Observations during this study ('Normal Behavior' section, Würsig et al. 1982) suggest that bowheads get portions of their daily food requirement (1) from surface waters, (2) from the water column, and (3) near or at the bottom. The abundance of hydromedusae within the areas where bowheads feed suggests that these animals are an important part of the bowhead diet even though they have not been reported in bowhead stomach contents.

During the open water season, bowheads travel from the Bering Sea to the Beaufort Sea. Annual primary production and zooplankton biomass are higher in the Bering Sea, and in addition the turnover rate of carbon is faster in the Bering Sea. A detailed cost/benefit analysis for the migration would have to consider seasonal variation in zooplankton biomass in each area, effects of depth and plankton patchiness on food availability in each area, the energy cost of swimming, and the effects of different thermal regimes. Available data are inadequate for such an analysis. However, the generally greater productivity of the Bering Sea suggests that factors unrelated to the total amounts of food in those two areas may cause bowheads to move into the Beaufort Sea in summer.

INTRODUCTION

The prospect of offshore petroleum exploration and development activities in the Beaufort Sea has heightened concern regarding the potential disturbance of bowhead whales, Balaena mysticetus. In response to these concerns a two-year multi-tasked study, of which this report is a part, was initiated to examine the possible effects of acoustic and other stimuli associated with oil and gas development on the behavior of bowhead whales. The tasks include studies of the normal behavior of the bowhead; its responses to boat, aircraft and noise disturbance; and the characteristics of bowhead feeding areas. The 'Project Rationale, Design and Summary' section of this report (Richardson and Fraker 1982) outlines the background for the overall study and the reasons for including the present component.

This part of the study was designed to document the physical and biological characteristics of bowhead feeding areas. The main purpose was to determine whether bowheads concentrate their feeding in areas of high zooplankton biomass or in areas that are otherwise unusual. If so, feeding areas would be of particular importance to bowheads and would be worthy of special consideration if they were likely to be affected by offshore exploration for oil and gas.

Bowheads feed in both the eastern (i.e. Canadian) Beaufort Sea in summer and the western (Alaskan) Beaufort Sea in autumn. Only the latter area is of direct interest to U.S. regulatory agencies, but some types of field studies of bowheads are more practical in the former area (see 'Project Rationale, Design and Summary' section). Because of various logistic considerations, the present study was conducted in the Canadian portion of the Beaufort Sea.

There were previous indications that epibenthic and perhaps even inbenthic organisms form parts of the diet of bowhead whales (see below). During the course of this project, it became apparent that, at various times, bowheads feed at and near the surface, in the water column, and at or near the bottom (see 'Normal Behavior' section, Würsig et al. 1982). Thus, all parts of the water column are of interest in this study.

Objectives

The original objectives of the 'Feeding Areas' portion of this study, as outlined by BLM, involved the measurement of biological and physical characteristics of feeding areas and non-feeding areas in an attempt to identify factors that influence the distribution and selection of feeding places of the bowhead. We proposed broad-scale systematic sampling of zooplankton and physical measurements (temperature, salinity) at stations in areas where bowheads were common and uncommon, including repeated sampling twice during the season. This sampling program was to be coordinated with an observational study of the feeding behavior (and other behaviors) of the bowhead. However, because of budgetary constraints, and on the advice of BLM, the scope of the study was reduced; the number of samples to be collected and the variety of situations to be tested were reduced, and sampling was largely restricted to areas where bowheads were observed. A complementary study of zooplankton patchiness was also deleted from the plans.

The revised program involved an examination of the physical characteristics of the water and the biomass of zooplankton in areas where bowheads were common, and particularly in areas where they were observed to feed. The objective was to determine if bowheads tended to occur in regions of high zooplankton biomass or in regions with other unusual biological or physical features. The complementary observational study of bowhead behavior, including feeding behavior, was conducted more or less as originally planned (see 'Normal Behavior' section).

Review of Previous Knowledge

Feeding Behavior

Prior to the present study, knowledge about the feeding behavior of the bowhead whale was primarily from accounts by early arctic explorers and whaling captains and by studies of the morphology and function of the feeding apparatus. Scoresby (1820) provided a general description of the feeding behavior of bowhead whales; and Matthews (1978) gives a more elaborate description for right whales. Right whales typically feed by using a skimming technique (i.e. they scoop up food by swimming with their mouths open) and by swallowing the food retained in the mouth cavity (Nemoto 1970; Matthews 1978; Pivorunas 1979). This type of feeding behavior is attributed to the structure of the baleen plates (i.e. long, slender and elastic) and the shape of the jaw (Nemoto 1970; Matthews 1978).

Right whales (Eubalaena sp.), which are closely related to bowheads, appear to use this feeding technique in two basic ways: (1) skimming the surface layers, and (2) filtering plankton from the water column. Watkins and Schevill (1976, 1979) found that right whales often skim the surface of the water with mouths open, presumably filtering the plankton from the surface layer. In addition, they have observed right whales apparently feeding on plankton layers at some depth beneath the surface. Both skim feeding and water column feeding by bowheads were observed during this study (see 'Normal Behavior' section).

The presence of bottom-dwelling species (amphipods, fish, etc.) and pebbles in stomach content samples from bowheads provides evidence that some bowhead feeding takes place on or near the bottom (Johnson et al. 1966; Marquette 1977; Braham et al. 1980; Lowry and Burns 1980). Fraker et al. (1978) reported behavior of bowheads along the Yukon coast that suggested bottom or near-bottom feeding. The behavioral portion of the present study provides the first direct observations of bowheads engaged in feeding along the bottom (see 'Normal Behavior' section).

Right and bowhead whales are anatomically adapted to skim sparsely distributed zooplankton from large volumes of water, whereas other baleen whales (e.g., humpback, gray and fin whales) concentrate on denser patches of plankton and/or fish (Nemoto and Kawamura 1977; Nemoto 1970; Jurasz and Jurasz 1979; Pivorunas 1979). However, Watkins and Schevill (1976, 1979) found that right whales also concentrated their feeding in dense patches of zooplankton. The whales appeared to be able to detect and follow irregular shaped patches that were visible to Watkins and Schevill from the air. Calculations by Brodie (1981) suggest that bowheads may need to feed in concentrated patches of zooplankton in order to satisfy their energy requirements. The commercial whalers indicated that bowheads sometimes concentrated in patches or areas of 'brit' (dense zooplankton) (Scoresby 1820), but there have been no modern studies of this phenomenon in bowheads.

Bowhead Diet

Because bowheads are protected from commercial exploitation and presently are not taken by Canadian Inuit, no samples of stomach contents are available from the eastern Beaufort Sea. That area constitutes the main part of the summer range of the Western Arctic population, and is believed to be a major feeding area (Fraker and Bockstoce 1980). However, the bowhead's summer feeding range extends westward into the Alaskan Beaufort Sea in late summer and early fall. Residents of Kaktovik, Alaska, landed five bowheads in September and October 1979, and the stomachs of these specimens all contained relatively large amounts of planktonic food organisms (Lowry and Burns 1980). Similarly, two bowheads taken near Point Barrow in September 1976 contained planktonic organisms (Lowry et al. 1978).

Lowry and Burns (1980) found that the copepod *Calanus hyperboreus* was by far the most common food item consumed near Kaktovik. Euphausiids, almost exclusively *Thysanoessa raschii*, occurred in samples from four of the five whales and were dominant in two whales. Lowry et al. (1978) also found that euphausiids dominated the diet of two bowheads taken at Barrow. The mysid 'shrimp' *Mysis litoralis* was common in samples from three of the five Kaktovik stomachs (Lowry and Burns 1980). Another 22 species were identified from the five stomachs, but none of these comprised a major part of the stomach contents. The majority of these other species were 'epibenthic' amphipods.

Marquette et al. (1981) summarize present knowledge of the feeding ecology of bowhead whales in Alaskan waters in autumn and conclude that bowheads feed primarily on copepods, euphausiids and amphipods (both hyperiid and gammarid). Bowheads taken in Alaskan waters in spring usually have empty stomachs, but one stomach examined in 1977, one examined in 1979, and three of nine examined in 1980 contained some food items -- mainly copepods plus a few pteropods and other items (Marquette 1977, 1979; Braham et al. 1980; Lloyd Lowry, Alaska Dept. of Fish & Game, pers. comm.). Marquette et al. (1981) conclude that migrating bowheads in spring do not feed extensively.

In the Davis Strait/Baffin Bay area, Brown (1868) reported that zooplankton, mainly copepods and to a lesser degree pteropods, were important components of the diet. Mitchell (1975) states (without presenting data) that bowheads consume mysids, amphipods and various small to medium sized zooplankton. Nemoto (1970) reported that right whales in the north Pacific feed mainly on swarming copepods (e.g., Calanus plumchrus and C. cristatus) and euphausiids (e.g., Thysanoessa inermis and T. raschii) and concluded that, in general, 'skimming type whales [right whales and bowheads] are distributed mainly in the waters where the copepods are dominant'.

Beaufort Zooplankton and Water Masses

Marine zooplankton forms an important part of food webs in the Arctic Ocean and peripheral seas. Many zooplankters feed on phytoplankton and are thus responsible for most of the secondary production that occurs in these seas. The results of various studies carried out in the Beaufort Sea indicate that marine zooplankton and epibenthic invertebrates form a fundamental trophic link between phytoplankton and vertebrates. These food chains can be very short and lead quickly to the higher vertebrate consumers such as fish (Craig and Haldorson 1981), birds (Johnson and Richardson 1981), and marine mammals (Lowry et al. 1979; Davis et al. 1980). For example, the herbivorous copepod Calanus hyperboreus was by far the most common species eaten by five bowhead whales taken off Kaktovik, Alaska (Lowry and Burns 1980).

The zooplankton of the Arctic Ocean has been separated into several groups based primarily on their association with one of the three major arctic water masses: (1) the Arctic surface layer; (2) the Atlantic layer; and (3) the Arctic bottom layer. Hopkins (1969), who sampled from ice islands T-3 and Arlis II, found the Arctic surface water (depths 0-200 m) to be more 'productive' (56 individuals/m^3; 0.62 mg dry wt./m^3) than the Atlantic layer (depths 200-900 m; 13 individuals/m^3; 0.14 mg dry wt./m^3) or the Arctic deep water (depths >900 m; 3-4 individuals/m^3; 0.04 mg dry wt./m^3). In all cases copepods (particularly the genus Calanus) contributed most to zooplankton biomass; their average percentage contributions in the Arctic surface, Atlantic and Arctic deep layers were 83, 85, and 89%, respectively (Hopkins 1969). Similarly, in the eastern high Arctic, copepods comprised 79% of the total zooplankton biomass in the upper 150 m of Lancaster Sound and 84% in the upper 150 m of northwestern Baffin Bay (Sekerak et al. 1976, 1979; Buchanan and Sekerak 1982). Other groups that occasionally contribute significantly to zooplankton biomass include hydromedusae, amphipods, mysids, chaetognaths, pteropods, decapods, and larvaceans (Hopkins 1969; Sekerak et al. 1976, 1979; Buchanan and Sekerak 1982). Any of the above groups may be locally abundant and at times overshadow the importance of copepods.

Based on horizontal and vertical distribution patterns and physical measurements, Grainger (1965) described three major groups of zooplankton in the Beaufort Sea and adjacent marine waters. One group is characteristic of inshore waters and the upper 100 m of offshore waters. The species that comprise this group are typically tolerant of a wide range of temperatures and salinities, and include the medusae *Aglantha digitale* and *Aeginopsis laurentii*, the pteropods *Limacina helicina* and *Clione limacina*, the combjelly *Beroe cucumis*, and several species of copepods--*Calanus glacialis*, *C. hyperboreus*, *Microcalanus pygmaeus*, *Pseudocalanus minutus*, *Metridia longa* and *Oithona similis*. A second group is characteristic of nearshore brackish waters along the coastlines of the Beaufort and Chukchi Seas and includes the medusae *Obelia* sp. and *Euphysa flammea*, and the copepods *Eurytemora herdmani*, *Acartia clausi*, and *Limnocalanus macrurus*. The third group is restricted to colder, more saline offshore deep waters. Species in this group include the ostracod *Conchoecia maxima*, and the copepods *Gaidius tenuispinus*, *Heterorhabdus norvegicus*, *Scaphocalanus magnus*, and *Chiridius obtusifrons*.

Although the highest density and biomass of zooplankton occur in the Arctic surface layer, the greatest diversity is found in the deeper Atlantic water mass. Most of the species in the latter water mass are not abundant (Hopkins 1969; Redburn 1974).

Grainger (1975) sampled zooplankton in the southeastern Beaufort Sea between Herschel Island and Cape Dalhousie and found that the highest densities of zooplankton occurred in sheltered bays (e.g., Mason Bay, Tuktoyaktuk Harbour and Liverpool Bay). Although densities were high in these areas, species diversity was low. The copepods *Acartia clausi*, *Eurytemora herdmani*, *Pseudocalanus minutus*, and *Limnocalanus macrurus* accounted for most of the organisms present. Numbers of zooplankters were lowest near and in the mouth of the Mackenzie River where freshwater forms such as *Daphnia*, *Diaptomus* and *Bosmina* predominated. Intermediate numbers of zooplankton were found farther offshore in the zone where oceanic waters and water from the Mackenzie River mix.

Comparisons of the standing crop of zooplankton within different regions of the Beaufort Sea and among various areas of the arctic and subarctic are confounded by a series of factors and variables. These include large (100's of metres) or small (10's of metres) scale patchiness in the abundance and distribution of zooplankton species, the wide variety of net and mesh sizes used in various studies, and the fact that most authors report their results in terms of numbers rather than biomasses. However, Grainger (1975) concluded that zooplankton standing stock in the southern Beaufort Sea was low in comparison to that in most other northern marine waters. Higher standing stocks have been found in Frobisher Bay (Grainger 1971) and Lancaster Sound (Sekerak et al. 1976).

Approach

The planned field program for 1980 involved a 1-month charter (16 August to 15 September) of a boat in the 14-m class. The intent was to sample close to bowheads, and occasionally at other locations where bowheads were not observed, using a variety of gear (e.g., horizontal and vertical tow nets, drop net sampler, echosounder, etc.). The above approach had to be modified because of various logistical problems. By the date of contract award (30 June 1980), no one vessel with the required characteristics was available for the entire 16 Aug. - 15 Sept. period. It was necessary to initiate fieldwork on 31 July, when a boat (the 'Ungaluk') was to be available. Because of the resulting shortened lead-time and late delivery of some equipment, echosounder work and horizontal tows could not be done. Vertical tows, physical measurements and some drop-net samples were obtained, but the efficiency of this work was hampered by various boat difficulties. Esso Resources Canada Ltd. kindly loaned us one of their vessels, the 'Imperial Sarpik', for several days when we would otherwise have been boatless.

In 1981 the field sampling program was organized around a 45-day charter (28 July-10 September) of a 12-m class boat (the 'Sequel') provided by Beaufort Environmental Support Services Ltd. The 'Sequel' was used for disturbance and noise studies as well as for this work. The results of the 1980 study had confirmed that zooplankton was patchily distributed, and calculations suggested that bowheads may have to concentrate their feeding effort in the denser patches in order to acquire sufficient food. The 1981 sampling was conducted using (1) a high frequency (200 kHz) echosounder, which was capable of detecting layers of concentrated plankton, in conjunction with (2) horizontal tows to determine the extent and scale of zooplankton patchiness, and the density, biomass and identity of the animals comprising the patches. Samples were collected in areas where bowhead whales were common and in areas where they were uncommon to determine if the bowhead 'feeding areas' contained denser accumulations of zooplankters.

In both years, temperature and salinity profiles were taken at each station/date combination with a Hydrolab CTD. In 1981, near-surface turbidity was recorded with a Secchi disc. It was intended, on an opportunistic basis, to investigate zooplankton densities in the presence of 'fronts' or boundaries between warmer nearshore waters and cooler offshore waters, a phenomenon noted during the 1980 field season.

METHODS AND RATIONALE OF DATA COLLECTION

Results from the few studies on diets of right and bowhead whales suggest that they feed primarily on large marine zooplankton and, to a lesser degree, on bottom dwelling amphipods and fish. Therefore these organisms were selected as the focal points of the present study. To facilitate the capture of these larger zooplankton, we used a larger mesh size than would normally have been used in a zooplankton study (0.5 mm vs. 0.24 mm). An effort was made to collect representative zooplankton samples in areas where bowhead whales were observed feeding and also in non-feeding areas, in order to determine if bowhead whales select specific feeding areas or just feed randomly within their summer range. The sampling locations for the 1980 and 1981 field seasons are listed in Table 1 and shown in Figures 1 and 2.

Table 1. Summary of sampling locations, water depths, time and dates occupied, and types of samples collected in the southern Beaufort Sea from 14 August to 6 September 1980 and 31 July to 6 September 1981. CTD = conductivity, temperature profile; S = Secchi disc; HT = horizontal tow at depth indicated; VH = vertical haul, DN = drop net.

Station	Position	Water Depth (m)	Date	Time* (MDT)	Type of Sample
Off Richards Island, 1980					
1	69°56'N 134°23'W	12.0	14/08/80	0700	CTD, VH
2	70°00'N 134°16'W	17.0	14/08/80	0800	CTD, VH
3	70°01'N 134°04'W	20.0	14/08/80	0900	CTD, VH
4	69°56'N 134°55'W	17.0	24/08/80	1130	CTD, VH
5	70°04'N 134°19'W	25.7	26/08/80	1100	CTD, VH
6	69°59'N 133°56'W	19.3	26/08/80	2100	CTD, VH
7	69°59'N 134°18'W	13.5	26/08/80	2200	CTD, VH
8	69°56'N 134°18'W	10.2	26/08/80	2300	CTD, VH
King Point Stations, 1980					
9	69°07'N 138°00'W	5.5	20/08/80	1200	CTD, HT (3.0 m) DN (5.5 m)
9	69°07'N 138°00'W	6.8	21/08/80	1300	CTD, VH
10	69°09'N 138°00'W	20.0	20/08/80	1400	CTD, HT (3.0, 10.0 m), DN (20.0 m)
10	69°09'N 138°00'W	17.0**	21/08/80	1500	CTD, VH
9	69°07'N 138°00'W	7.5**	06/09/80	1400	CTD, VH
10	69°09'N 138°00'W	16.3**	06/09/80	1600	CTD, VH
Off Tuktoyaktuk and Richards Island, 1981					
N-1	69°50.7'N 133°20.0'W	14.0	31/07/81	1910	CTD, S, HT (0, 5, 10 m)
			12/08/81	0020	CTD, S, HT (0, 5 m)
L-1	69°55.6'N 133°22.8'W	20.0	01/08/81	0950	CTD, S, HT (0, 5, 15 m)
			11/08/81	2200	CTD, S, HT (0, 5, 10 m)
			06/09/81	1223	CTD, S, HT (0, 5, 15 m)
N-2	70°02.0'N 133°55.0'W	23.0	05/08/81	1125	CTD, S
			06/08/81	1330	CTD, S, VH

Continued...

Table 1 Concluded.

Station	Position	Water Depth (m)	Date	Time* (MDT)	Type of Sample
N-3	70°09.5'N 134°29.5'W	35.0	06/08/81	1040	CTD, S
N-4	69°36.4'N 133°04.8'W	5.0	10/08/81	1245	CTD, S, HT (0 m), DN
N-5	70°10.0'N 133°28.5'W	40.0	11/08/81	1200	CTD, S, HT (0, 20, 30 m)
N-6	70°05.2'N 133°25.6'W	32.0	11/08/81	1525	CTD, S, HT (0, 15, 20 m)
N-7	70°00.5'N 133°23.3'W	27.0	11/08/81	1900	CTD, S, HT (0, 15, 20 m)
N-8	70°02.8'N 134°30.0'W	20.0	14/08/81	1630	CTD, S, HT (0 m)
N-9	70°00.3'N 134°43.0'W	26.0	18-19/08/81	0006	CTD, S, HT (0, 2, 15 m)
N-10	70°02.6'N 134°48.5'W	27.0	19/08/81	1555	CTD, S, HT (0, 5, 15 m)
N-11	70°08.3'N 134°38.3'W	30.0	24/08/81	1635	CTD, S, HT (0, 5, 15 m)
N-12	69°57.3'N 133°52.0'W	17.0	24/08/81	2125	CTD, S, HT (0, 5, 15 m)
N-13	69°52.0'N 134°49.0'W	10.5	25/08/81	1410	CTD (0, 2.5 m), HT (10 m)

* Time of CTD, normally conducted just prior to net sampling.

** Depths and locations of stations 9 and 10 varied slightly because the presence of ice prevented resampling at the exact locations previously sampled.

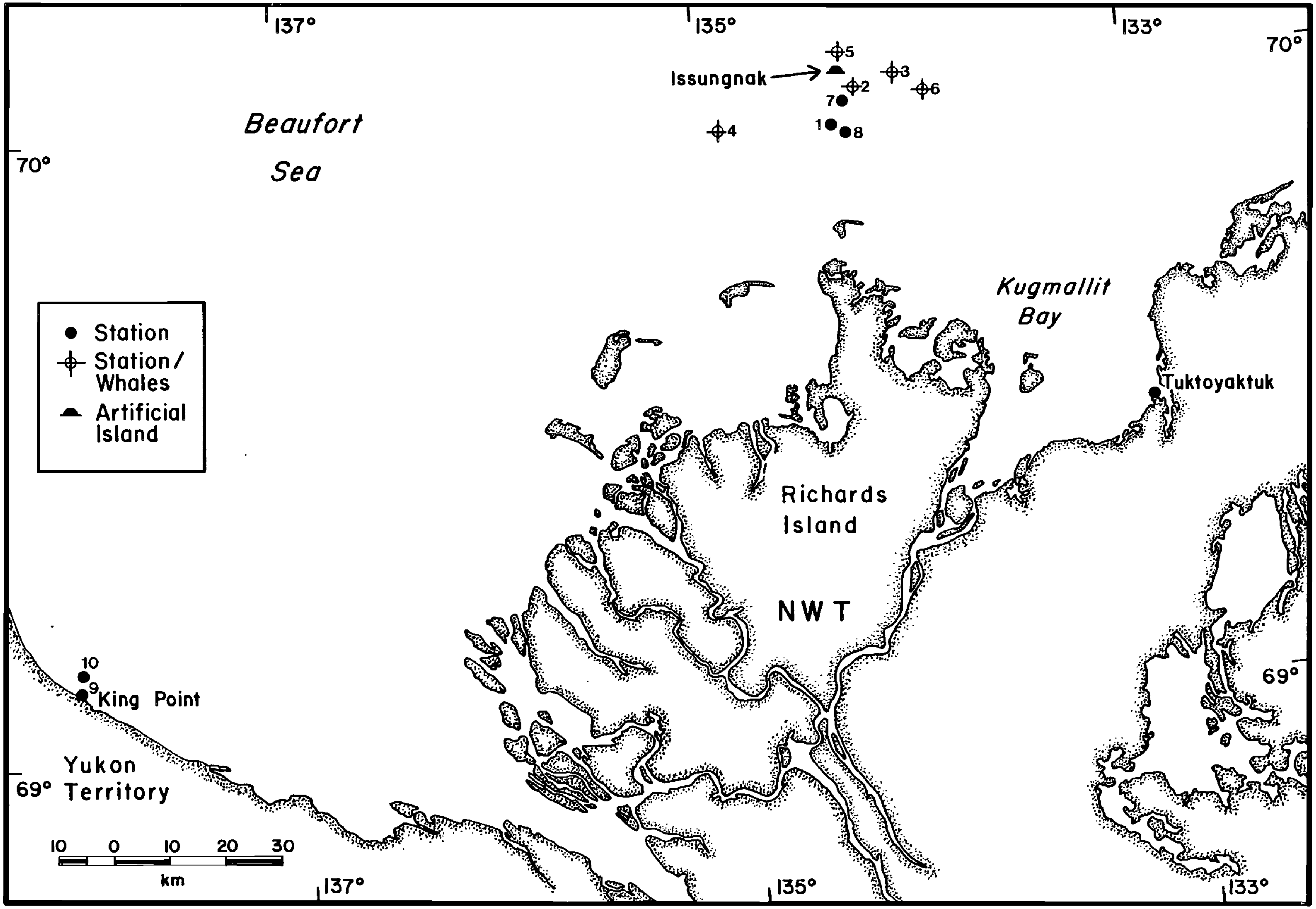


FIGURE 1. Locations of sampling stations in the southern Beaufort Sea, 14 August to 6 September 1980. Open circles represent whale-associated stations and closed circles are stations where whales were not observed during sampling.

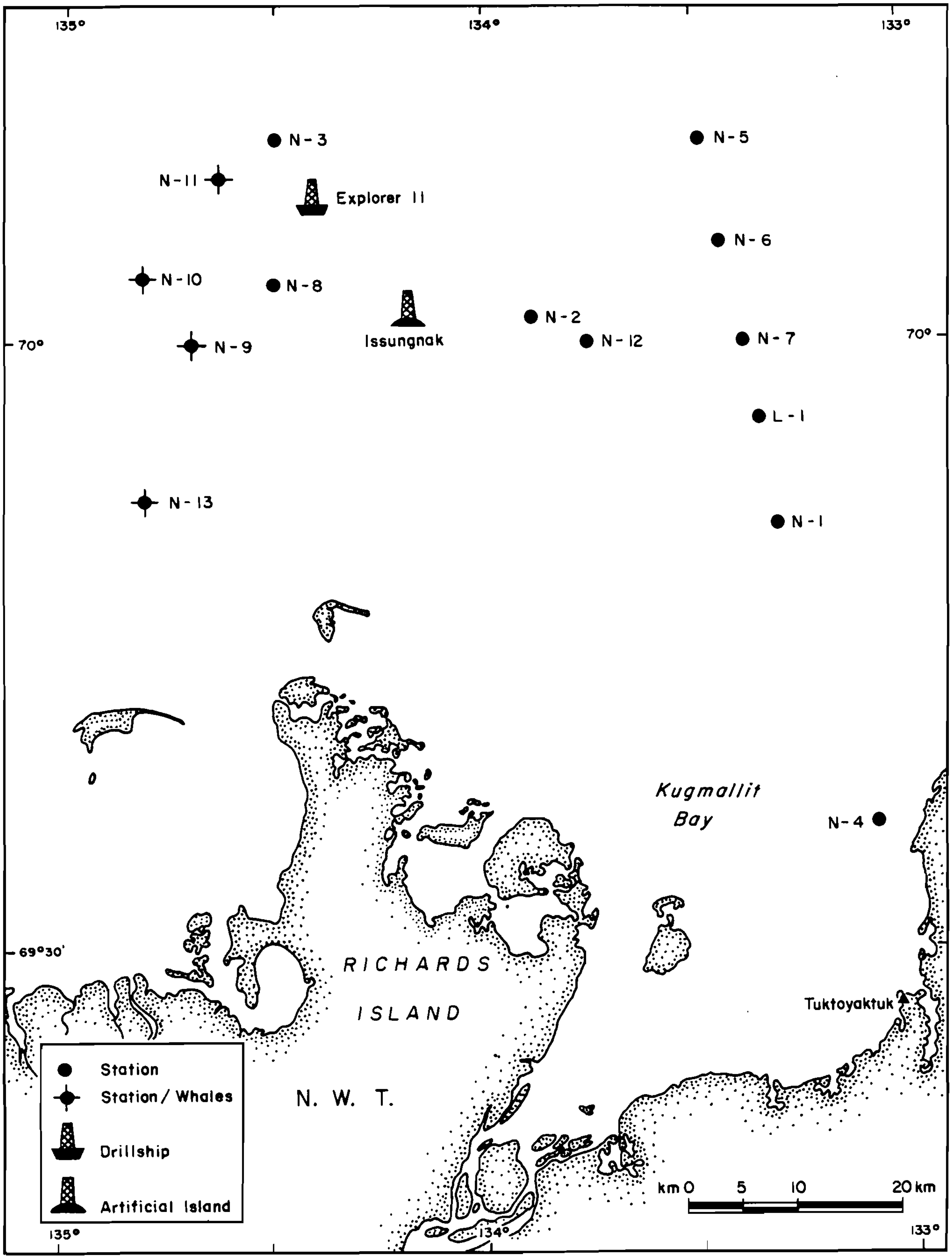


FIGURE 2. Locations of sampling stations in the southern Beaufort Sea, 31 July to 6 September 1981.

Field Methods, 1980

Sampling was conducted from a variety of ships and boats off Richards Island (northwest of Tuktoyaktuk) and off King Point along the Yukon coast (Fig. 1). Stations 1 through 3 were occupied using the 'Ungaluk', a 14-m wooden-hulled ketch; Stations 4 through 8 were sampled from the 'Imperial Sarpik', a 21 m steel-hulled crew boat. A Zodiac (5 m inflatable boat) was used at Stations 9 and 10 off King Point (Table 1; Fig. 1). Locations of the stations sampled from 'Ungaluk' were determined using a Magnavox MX1105 Satellite/Omega system; those sampled from the 'Imperial Sarpik' were determined using the on-board radar; and those sampled from the Zodiac were determined using a land-based theodolite.

Vertical Tows

Off Richards Island, N.W.T., vertical zooplankton samples were collected using a 0.61 m diameter plankton net (mesh size, 0.5 mm) equipped with a flowmeter (Inter Ocean Model 313). The net was towed at approximately 1 m/s and it sampled the water column during both ascent and descent.

Off King Point, Y.T., vertical zooplankton samples were collected in a similar fashion using a hand winch in a Zodiac. During the 6 September sampling period, a 0.5 m diameter net (mesh size, 0.24 mm) was used in place of the 0.61 m net described above.

At each station six replicate vertical tow samples were collected and the volumes filtered were calculated from the flowmeter readings.

Horizontal Tows

On one occasion, horizontal zooplankton samples were collected at the two King Point stations. Two Miller samplers (0.5 mm mesh) were towed simultaneously at 3.0 m depth at the shallow nearshore station (Stn. 9) and at 3.0 and 10.0 m depths at the deeper offshore station (Stn. 10). Six replicate samples were obtained for each of these three station/depth combinations. The Miller samplers were towed for 10 min at approximately 1.5 m/s and the volume filtered was estimated using mouth area (0.009 m^2) and the duration and speed of tow. Miller (1961) found that the differences between measured and theoretical filtration rates were negligible with these samplers.

Drop Net Samples of Epibenthos

A modified drop net sampler 0.5 m in diameter and with a net 1 m long (1.0 mm mesh) was used to sample epibenthic invertebrates at Stations 9 and 10 at King Point. Griffiths and Dillinger (1981) describe the net and the sampling procedure. This net is designed to obtain unbiased samples of fast-moving epibenthic species, especially mysids and some amphipods.

Temperature and Salinity

Temperature (± 0.10°C) and conductivity (± 0.1 millimhos/cm) were measured routinely at depths of 0, 2, 5, 7 and 10 m, and at 5 m intervals from 10 m to the bottom. Measurements were obtained with a Hydrolab System 8000 at each station/date combination listed in Table 1. Conductivity readings were converted to salinity values according to conversion formulae contained in Lewis and Perkin (1981).

Field Methods, 1981

Sampling was conducted from the MV 'Sequel' (12.5 m L.O.A.) at 14 separate oceanographic stations north and northwest of Tuktoyaktuk (Fig. 2; Table 1). Positions were determined by Faruno radar (24 n.mi. range) and dead reckoning; when possible, positions were confirmed by satellite navigator (Polar Research Laboratory Inc.), by a VLF/Omega system on the Islander aircraft used for observing bowheads, and by other vessels. In the presence of whales (Stations N-9, N-10, N-11, N-13), the vessel was guided and positioned by the Islander.

Horizontal Tows

Horizontal tows were the primary sampling technique for zooplankton collection in 1981. This approach was chosen because it provides information about zooplankton at specific water depths. We suspected that zooplankton would be concentrated in layers in areas where whales feed, so it was important to use a method that provided samples from particular depths. Double-oblique or vertical tows provide more reliable estimates of zooplankton abundance and biomass throughout the water column, but they cannot determine biomass at particular depths, and are of limited value in determining overall biomass for zooplankton that concentrate at particular depths.

The horizontal tows were conducted at 15 station/date combinations using 60 cm diameter nets (505 µm mesh) equipped with closing bridles, General Oceanics tripping mechanisms, and torpedo-style flowmeters. Nets were set at selected depths while the vessel was underway by monitoring wire angle and wire out. Depth selection (normally surface, and selected mid-water and near-bottom depths, Table 1) depended on the existence of potential zooplankton layers and instructions from the aircraft concerning concurrent whale feeding behavior. Once set, the nets were towed for 5 min at 3.7-5.6 km/h, closed by messenger, and then retrieved. All tows were conducted during daylight hours. Three replicate tows were performed at each depth.

Echo Sounding

In an attempt to delineate zooplankton concentrations, hydroacoustic observations of zooplankton abundance were made routinely while we steamed to and from oceanographic stations, and during some of the horizontal tows. The areas covered are discussed in relevant sections of the 'Results'. We used a Ross Fine Line Depth Recorder (Model 250-M) and Ross Fine Line Transducer (Model Surveyor 200 B, 200 kHz, 22° beam width). During sounding operations, the start time and position, vessel's heading and speed (normally 15 km/h), and finish time and position were recorded. After a series of trial runs to determine optimum settings, the following equipment settings were maintained in order to obtain comparable recordings:

Paper Speed:	7 1/2 inches/hour (19.05 cm/h)
Pulse:	short
Range:	0-50 m
Sensitivity:	5
Fine Line:	2

Drop Net Samples of Epibenthos

A modified drop sampler (0.5 m diam., 1 m long, 1.0 mm mesh) was used to sample epibenthos at a single station (N-4). The net and sampling methods are described in detail in Griffiths and Dillinger (1981).

Temperature, Salinity and Turbidity

At each station/date combination (Table 1), temperature (± 0.1°C) and conductivity (± 0.1 millimhos/cm) were measured throughout the water column at depths of 0, 2.5, 5, 7.5, 10, 15, 20, 25, 30 and 40 m, with the lowest depth depending on water depth. Equipment and procedures were the same as in 1980.

Relative measures of turbidity were obtained by lowering a Secchi disc at every 1981 station listed in Table 1. A standard (20-cm diameter) disc with black and white quadrats was lowered on the shaded side of the vessel until no longer visible; the 'depth of disappearance' was recorded by the same observer on each occasion.

Laboratory Techniques

All samples were preserved in 10% formalin in the field and were shipped to the laboratory for analyses.

The 1980 samples were sieved through a 1.024 mm mesh nylon screen, washed with water, and examined under a low-power binocular microscope. Individual organisms were identified to species where possible, counted and wet weighed to the nearest mg using a Mettler PL 1200 electronic balance. These data were used to calculate the biomass/m^3 of zooplankton in the water column and the biomass/m^2 of epibenthic invertebrates on or near the bottom.

In 1981, similar laboratory techniques were used with the following exceptions. All samples were strained through a 0.569 mm nylon mesh screen. Only samples collected at bowhead 'feeding locations' and at nearby sites where no bowheads were observed were identified to species; all other samples were identified only to major groups (e.g. copepods, amphipods, etc.). In cases where large numbers (>100 of any group) of organisms were encountered, the sample was subsampled, using a Hensen-Stemple pipette, so that no more than 100 individuals of any group were processed.

Limitations and Biases

The procedures for sampling of marine zooplankton contain inherent errors that must be taken into account when interpreting the results. Limitations and biases of the sampling techniques utilized in this study are discussed below.

Vertical and Horizontal Tows

The results of vertical and horizontal zooplankton tows are often underestimations of the true zooplankton biomass because of a variety of factors. Some of the more important sources of error are listed below:

1. The water flow pattern at the mouth of the net. Typically a conical net with no mouth-reduction cone samples less than 100% of the water presented to it. This problem is partially taken into account by the use of a flowmeter; however, underestimates still result because of the placement of the net behind solid structures such as the bridle apex, as was necessary in this study.

2. The filtration efficiency of the net. Monofilament nets are subject to the progressive accumulation of residual plankton, which causes the net to clog up more rapidly than normal. This reduces the amount of water filtered. Because of this problem, high densities of zooplankton are more seriously underestimated than are low densities.

3. The net avoidance behavior of zooplankters. Some of the larger zooplankters (e.g. amphipods, mysids, euphausiids) are very mobile and can actively avoid a net by moving out of its path.

4. Zooplankton patchiness. Zooplankton may concentrate into dense 'clumps' or discrete layers. These aggregations are often missed by surface-operated techniques.

Drop Net

This net has proven to be an excellent sampling device for epibenthic invertebrates. Diver observations of the operation of the drop net indicate that the move-and-freeze evasive behavior of mysids does not prevent their capture (Griffiths and Dillinger 1981). The drop net is at maximum velocity just before it strikes the bottom and seals against the substrate. Pursing of the net's bottom causes mysids and amphipods to move upward and into the bag. The drop net does not sample inbenthic organisms effectively because the pursing operation only scrapes the substrate.

Laboratory Analysis

Limitations and biases encountered during the sorting and weighing of samples are discussed in some detail by Griffiths and Dillinger (1981) and Sekerak et al. (1979).

RESULTS AND DISCUSSION

The data on temperature and salinity of the water masses in the study area as well as the biomasses and species composition of zooplankton and epibenthos are presented below for both the 1980 and 1981 field seasons.

In 1980, vertical hauls were the primary technique used for zooplankton collection. The results from these samples suggested that bowheads must concentrate their feeding in areas with aggregations of zooplankton in order to get their daily ration. As a consequence, the 1981 sampling program was altered to concentrate on horizontal tows. The emphasis in this report is on the 1981 results because these better describe the presence of zooplankton aggregations.

Certain limitations should be kept in mind when interpreting the results. Differences in species composition, abundance, and biomass of zooplankton among parts of the study area (e.g. places where whales were and were not seen) are not easily determined because of small scale patchiness in zooplankton distribution, and changes in zooplankton abundance and biomass with time.

Temperature, Salinity and Turbidity, 1980-1981

Temperature and Salinity

The results of standard CTD profiles taken synoptically with zooplankton samples during 1980 and 1981 are shown in Figures 3 and 4. The ranges and mean values of temperature and salinity encountered at comparable stations and depths during 1980 and 1981 are presented in Table 2.

In both years of the study, the nearshore, shallow water of the southern Beaufort Sea was characterized by a warm, brackish water layer overlying a colder, more saline layer. Depths of the two layers varied within and between years, although the thermo- and halocline typically occurred between 7.5 and 15 m in both years (Figs. 3 and 4).

During 1981, the gradient between the two layers was most pronounced in late July and early August, so much so that it produced a well-defined trace on the echo sounder chart during this period (Figs. 4a and 5). This phenomenon is commonly found during hydroacoustic sampling (Forbes and Nakken 1972; FAO 1980). By mid-August and through to early September 1981, prolonged periods of high winds had tended to lessen this layering effect (Fig. 4a).

The warm brackish surface waters common to the whole study result from a combination of (1) the outflow of warm fresh water from the Mackenzie River and (2) solar warming and ice melt in shallow nearshore waters. The areal extent and distribution of this surface layer are influenced by both periodic phenomena (e.g. seasonal cycle of river discharge, silt load) and non-periodic phenomena (e.g. winds and summer ice cover) (Herlinveaux and de Lange Boom 1975; Fraker et al. 1979). The cold saline bottom water in the nearshore region is derived from Arctic surface water which extends from the bottom of the above-described surface layer to about 150 m (Herlinveaux and de Lange Boom 1975).

It is interesting to note that, in 1981, bowhead whales were first observed in the area north of Richards Island in mid August, while in 1980 the first observations in the same area were made in early August. (There

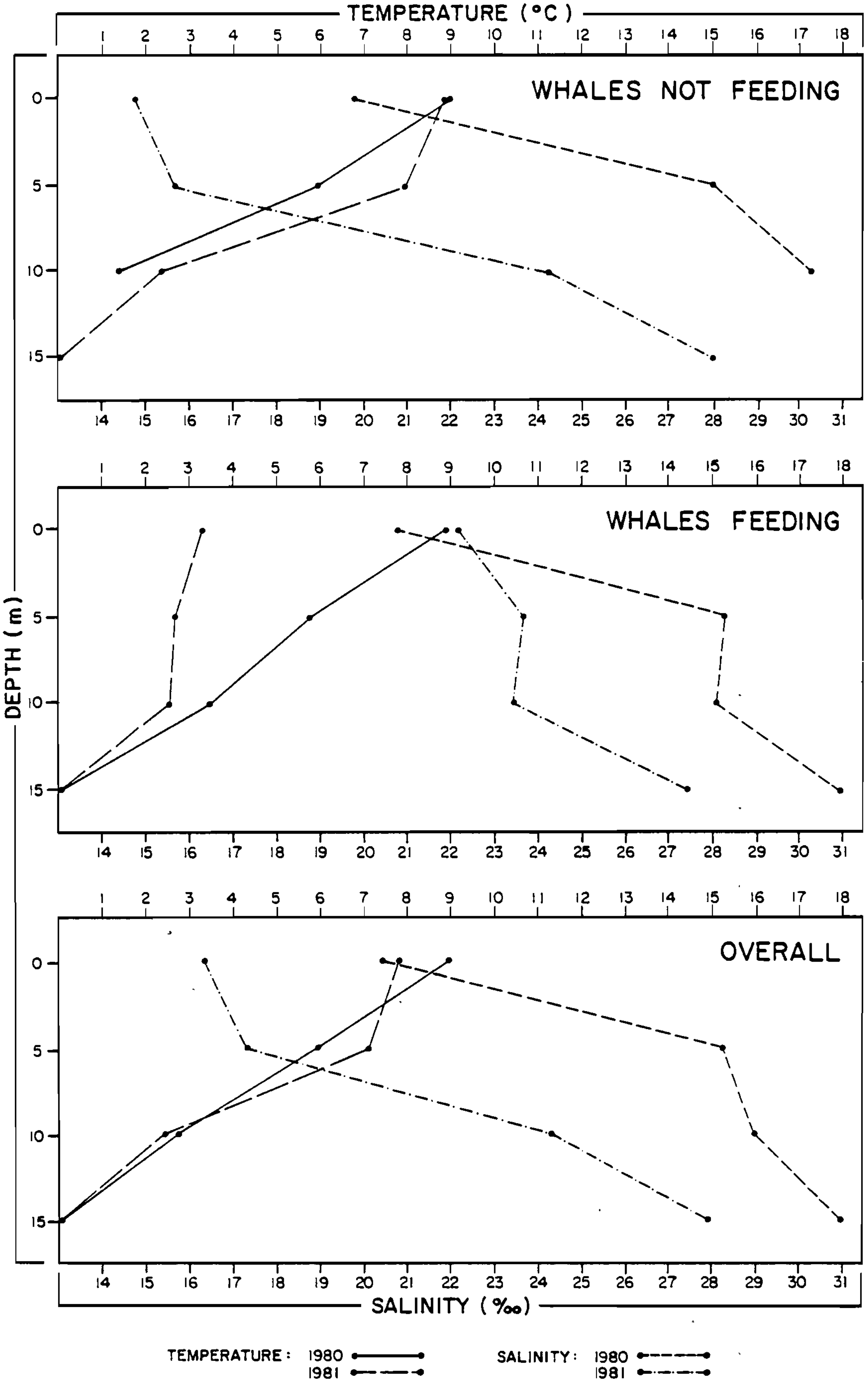


FIGURE 3. Mean temperatures and salinities at selected stations off the Mackenzie Delta and Tuktoyaktuk Peninsula in late summer of 1980 and 1981. Based on data contained in Table 2.

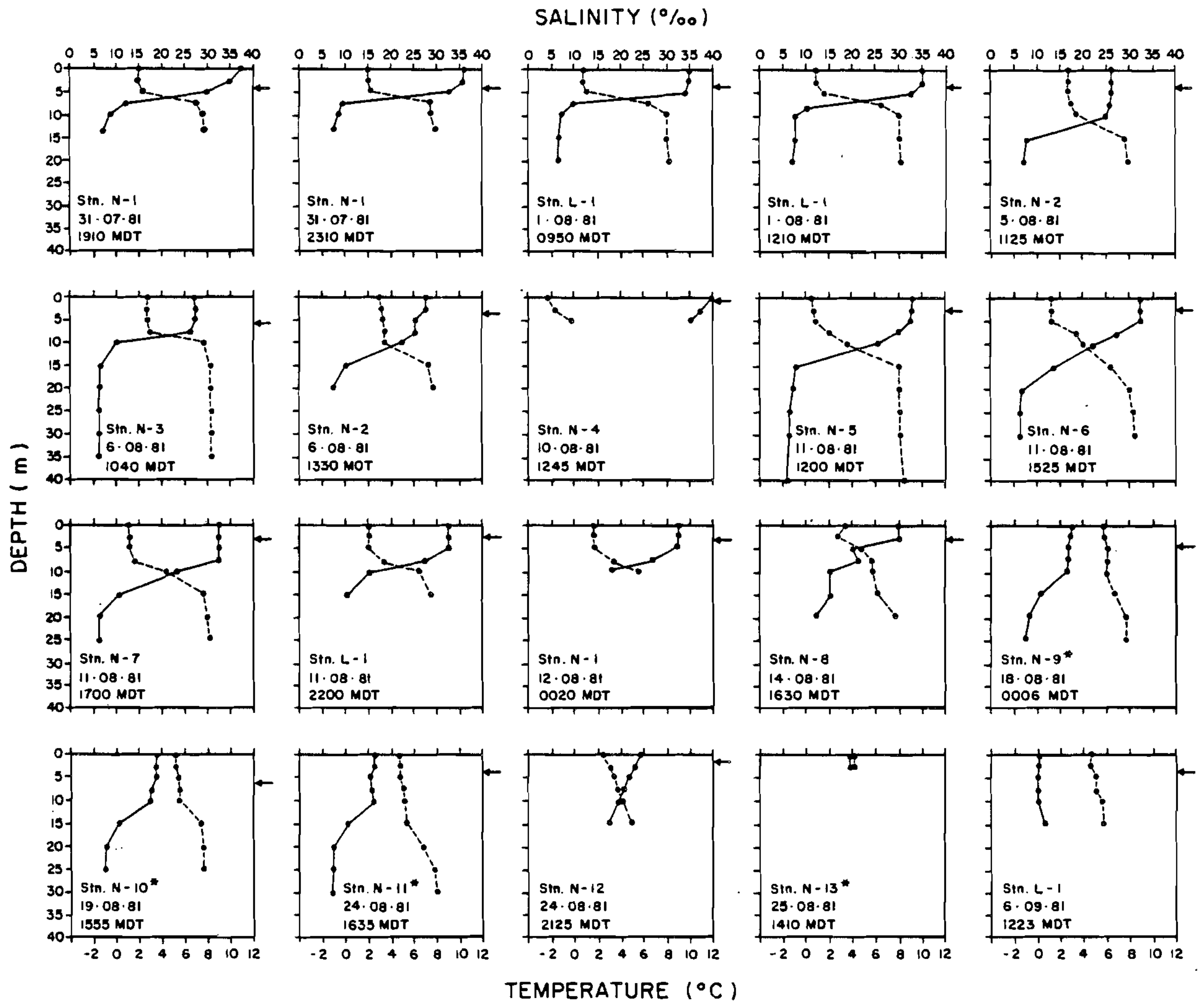


FIGURE 4a. Temperature (——, °C) and salinity (---, ppt) profiles for 1981 stations from the southern Beaufort Sea. Secchi depths (←—) are shown on right hand side. * indicates stations at which bowheads were observed.

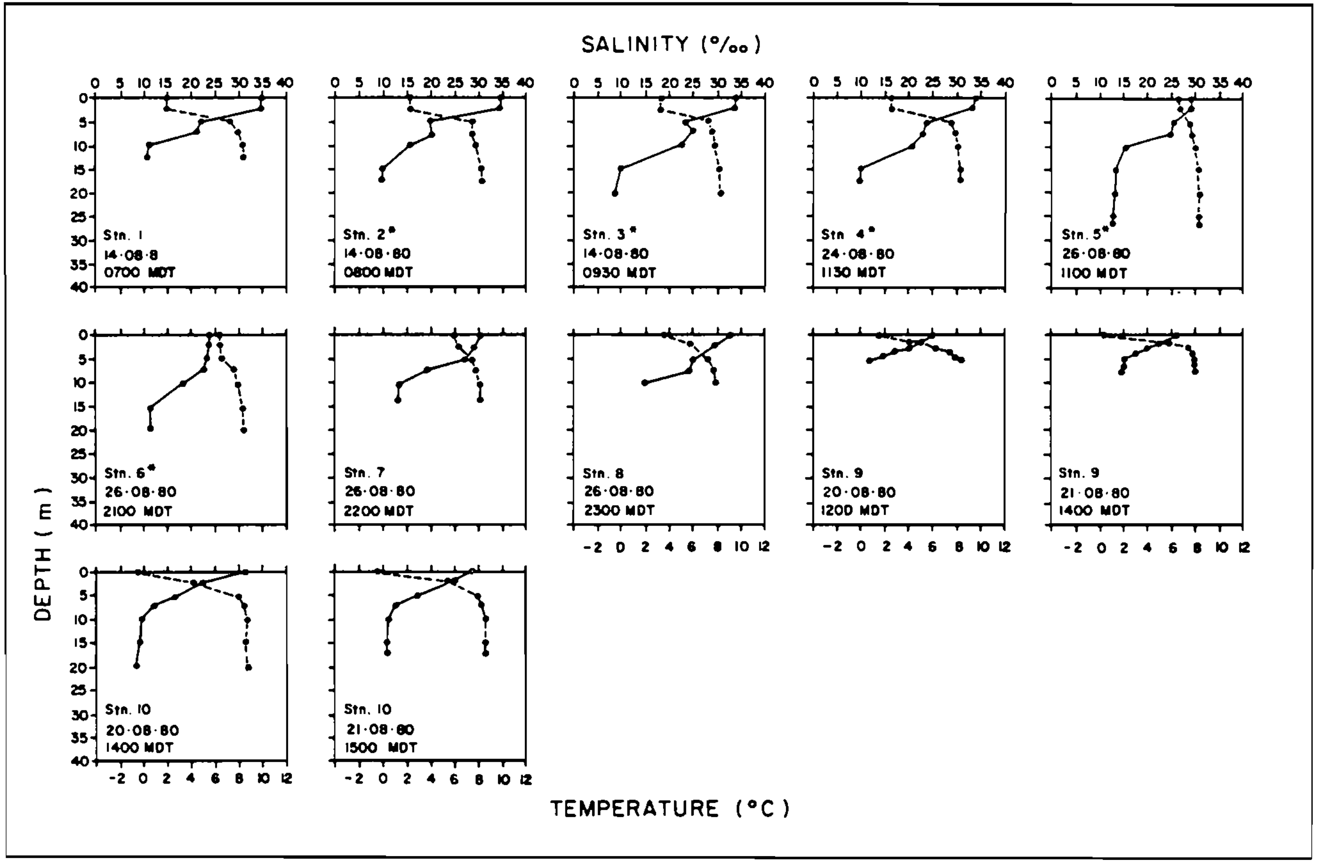


FIGURE 4b. Temperature (——, °C) and salinity (---, ppt) profiles for 1980 stations 1-10 from the southern Beaufort Sea, 14-26 August. All profiles are from surface to bottom. * indicates stations at which bowheads were observed.

Table 2. Comparison of temperature and salinity means (±S.D.) and ranges encountered at selected depths during 1980 and 1981. King Pt. Stations (1980) and 1981 Stations N-4 (a highly estuarine location) and L-1 (Sept. sampling) have been excluded from the comparison since equivalent locations and times were not sampled in both years.

	OVERALL				WHALES FEEDING				WHALES NOT FEEDING			
	Temp. °C		Salinity (ppt.)		Temp. °C		Salinity (ppt.)		Temp. °C		Salinity (ppt.)	
Depth	1980	1981	1980	1981	1980	1981	1980	1981	1980	1981	1980	1981
0 m Range	7.7-9.9	2.6-11.3	14.77-26.73	11.08-24.54	7.7-9.8	2.6-3.8	15.85-26.73	19.67-24.54	8.1-9.9	5.5-11.3	14.77-25.09	11.08-17.96
$\bar{x}$	8.9	7.8	20.40	16.36	8.9	3.3	20.80	22.20	9.0	8.9	19.82	14.80
S.D.	0.9	2.8	4.95	3.78	1.0	0.6	5.39	2.06	0.9	1.7	5.16	2.21
N	8	19	8	19	5	4	5	4	3	15	3	15
5 m Range	4.2-7.6	2.1-9.7	27.23-29.60	12.05-25.46	4.2-7.6	2.1-3.5	27.23-29.60	22.23-25.46	5.0-6.9	4.5-9.7	27.66-29.00	12.05-22.02
$\bar{x}$	5.9	7.1	28.25	17.03	5.8	2.7	28.33	23.72	6.0	8.0	28.10	15.70
S.D.	1.1	2.7	0.77	3.94	1.2	0.7	0.84	1.63	1.0	1.9	0.77	2.64
N	8	18	8	18	5	3	5	3	3	15	3	15
10 m Range	0.6-5.1	-1.2-6.3	29.82-30.76	18.17-29.83	2.2-5.1	2.2-2.9	20.11-30.33	23.54-25.32	0.6-2.1	-1.2-6.3	29.82-30.76	18.17-29.83
$\bar{x}$	2.7	2.4	28.96	24.29	3.5	2.6	28.12	23.45	1.4	2.4	30.35	24.26
S.D.	1.5	2.6	3.59	3.95	1.2	0.4	4.48	0.88	0.8	2.8	0.48	4.34
N	8	18	8	18	5	3	5	3	3	15	3	15
15 m Range	-0.5-0.6	-1.5-2.9	30.62-31.20	22.58-30.77	0.5-0.6	0.0-0.2	30.62-31.20	26.88-28.32	-	-1.5-2.9	-	22.58-30.77
$\bar{x}$	0.02	0.03	30.95	27.94	0.02	0.1	30.95	27.48	-	0.01	-	28.07
S.D.	0.4	1.4	0.23	2.18	0.4	0.1	0.23	0.75	-	1.6	-	2.45
N	5	14	5	14	5	3	5	3	-	11	-	11

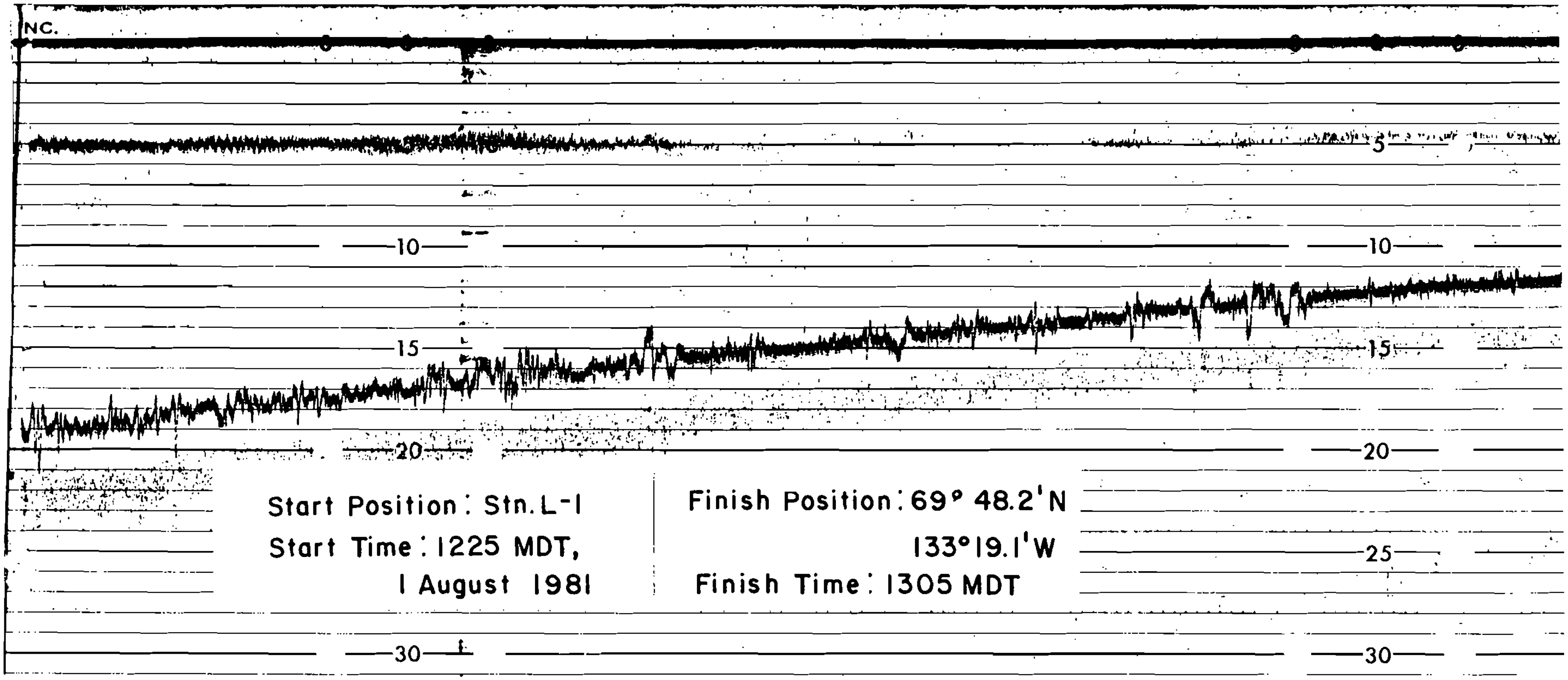


FIGURE 5. Echo trace showing layer at 5 m depth. Layer corresponds to the strong thermo- and halocline shown in Figure 3 and was probably caused by the strong density gradient.

were numerous whale reconnaissance and survey flights in the area throughout all of August in both years.) In 1981, the upper 15 m of water was generally less saline than in the same area during 1980 (Fig. 3; Table 2). It does not seem likely that the between-year differences in salinity *per se* altered the distribution of bowhead whales since both sets of salinities are well within the range that these whales would encounter during their seasonal migrations. However, the salinity differences may be a reflection of different water mass characteristics in the area and thus different species composition of zooplankton. Previous zooplankton studies conducted in this region suggest that the species in these waters are associated with either the nearshore brackish water or with the Arctic surface water layer (Grainger 1965, 1975).

Turbidity

Figure 4a shows Secchi depths for the 1981 sampling stations. The Secchi disc readings were obtained to assess relative differences in turbidity due to sediment load and/or phytoplankton. Within the present study area (a soft-bottomed, shallow water area within the influence of the Mackenzie River plume), the primary factors that determine the Secchi depth are wind and the sediment load transported by the Mackenzie River. Secchi depths varied from 0.5 m at the shallowest station (Station N-4) to 6 m at the deeper offshore stations (Station N-3 and N-10). However, there was no consistent pattern for the Secchi depths when all stations were considered. For example, one of the deepest, farthest-offshore stations (Station N-5) had a Secchi depth of only 2.5 m on 11 August 1981. The average Secchi depth (excluding the very shallow inshore Station N-4) was 3.7 ± 1.4 m.

It is interesting that the Secchi depths tended to be deep early in the season (i.e. 4-5.5 m between 31 July and 6 August at Stations N-1, L-1, N-2 and N-3) and that they correspond to the depth of the warm, low salinity surface layer. The Secchi depths were also at their deepest (5 and 6 m) at two stations where bowheads were observed (Stations N-9 and N-10 on 18 and 19 August respectively).

Data are insufficient to relate turbidity to whale distribution but it is likely that, during comparable time periods, the waters of the study area were more turbid during 1981 than 1980. We infer this from the stronger winds that occurred in 1981 and the generally lower salinities in 1981 (possibly because of a greater influence from the Mackenzie River). Either factor could greatly increase turbidity and may have been a factor instrumental (either directly as a behavioral clue or indirectly by affecting food supplies) in keeping bowheads farther offshore in 1981 than in 1980.

Zooplankton

Zooplankton Results in 1980

Vertical zooplankton hauls taken off Richards Island, N.W.T., and King Point, Y.T., in 1980 showed that hydrozoans and copepods were the dominant groups, in terms of biomass, in the water column (range for total biomass: 1302-12 mg/m^3 wet wt). Five species of hydrozoans (*Halitholus cirratus*, *Euphysa flammea*, *Sarsia princeps*, *Aglantha digitale*, *Aeginopsis laurentii*) and five species of copepods (*Calanus hyperboreus*, *C. glacialis*, *Limnocalanus macrurus*, *Pseudocalanus minutus*, *Derjuginia tolli*) accounted for most of the biomass (Figs. 6 to 14).

The 1980 results showed that the dominant groups in the water column were hydrozoans and ctenophores, copepods, and to a lesser degree mysids (Figs. 6-14). In contrast, on or near the bottom, mysids and isopods were the dominant groups collected (Fig. 15) These zooplankton results, while not in total agreement with other zooplankton studies in the area, are generally consistent with previous findings. Most studies of arctic zooplankton have shown copepods to be the dominant group both in terms of numbers (Johnson 1956; Grainger 1965; Hopkins 1969; Grainger and Grohe 1975; Horner 1979) and biomass (Hopkins 1969; Sekerak et al. 1976, 1979). However, other groups (e.g., hydromedusae, chaetognaths, pteropods) may be locally abundant and at times may overshadow the importance of copepods (Sekerak et al. 1979). Each of the dominant groups found in the water column and on or near the bottom in 1980 is discussed below ('Major Species and Groups' section).

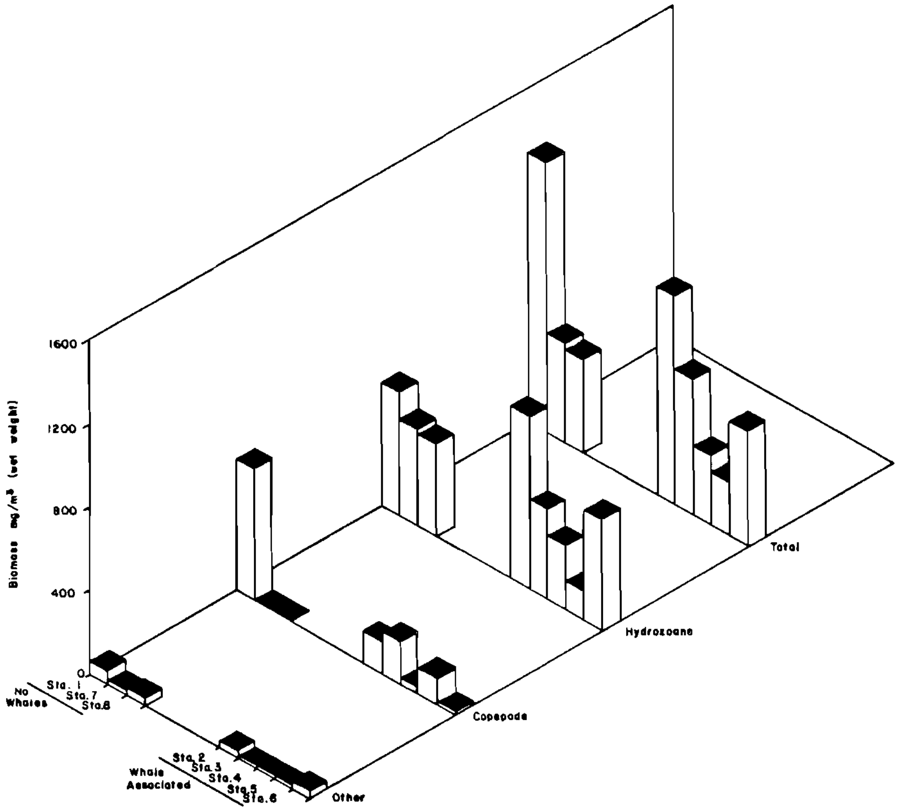


FIGURE 6. Biomass (mg/m^3 wet weight) of major groups of zooplankton collected in vertical tows off Richards Island, N.W.T., 14-26 August 1980. Whales were present at stations 2-6 and absent at stations 1, 7, 8. Each bar is based on six samples.

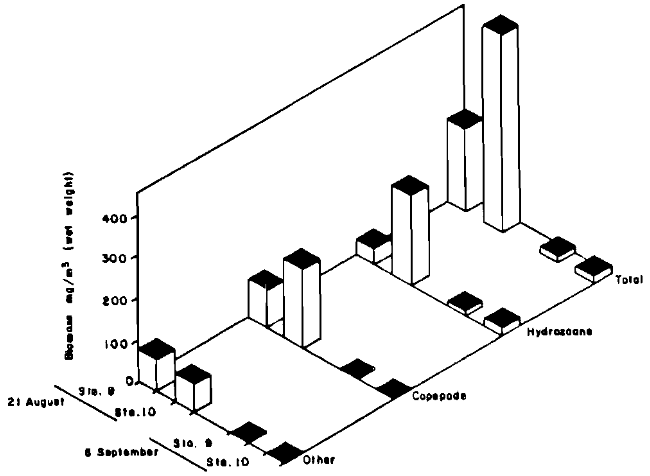


FIGURE 7. Biomass (mg/m^3 wet weight) of major groups of zooplankton collected in vertical tows off King Point, Y.T., 21 August and 6 September 1980. Each bar is based on six samples.

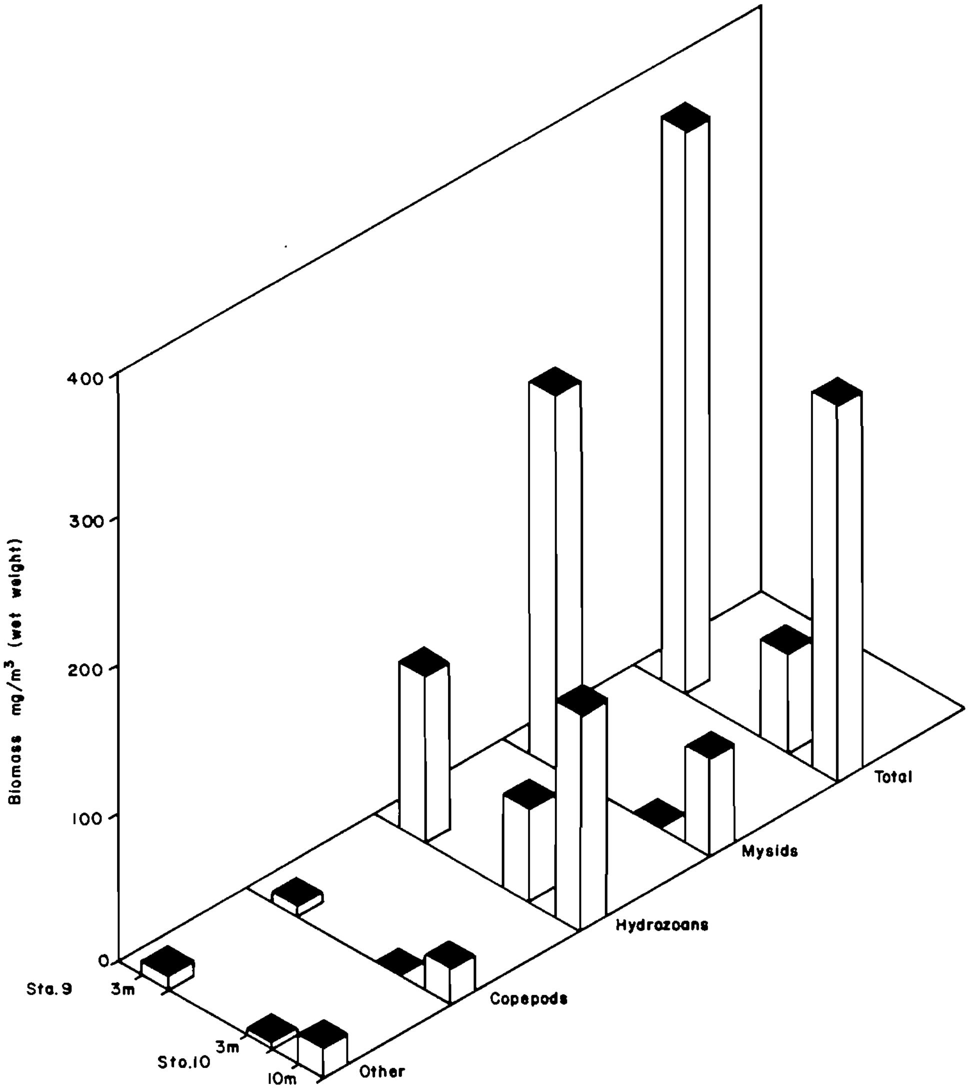


FIGURE 8. Biomass (mg/m^3 wet weight) of major groups of zooplankton collected in horizontal tows off King Point, Y.T., on 20 August 1980. Each bar is based on six samples.

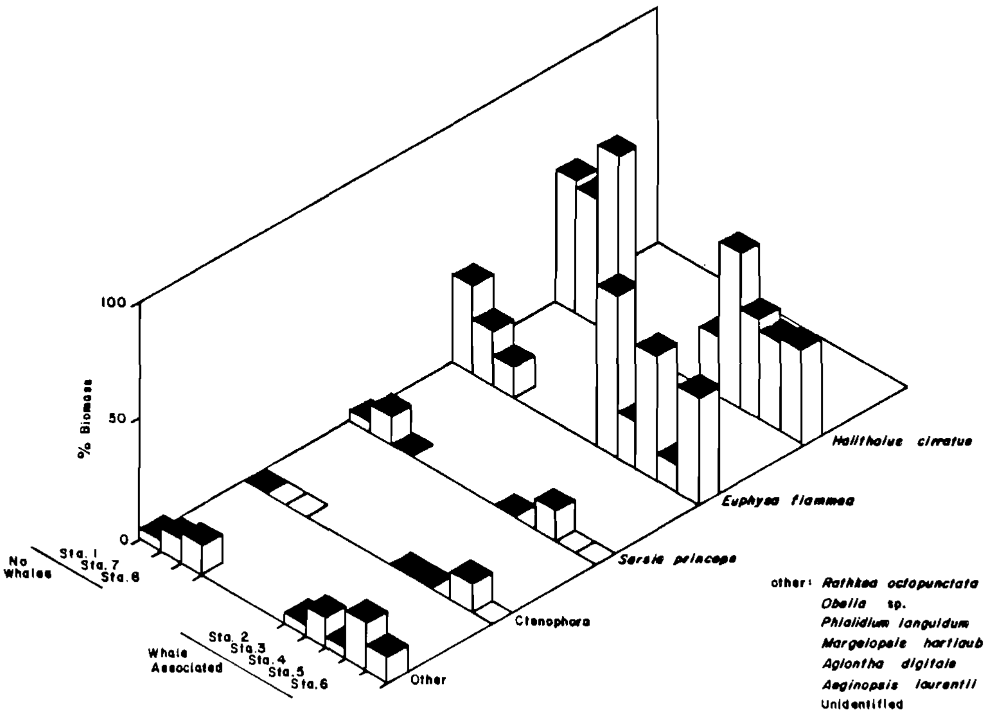


FIGURE 9. Percent composition of hydrozoan biomass collected in vertical tows off Richards Island, N.W.T., 14-26 August 1980. Whales were present at stations 2-6 and were not seen at stations 1, 7, 8. Each bar is based on six samples.

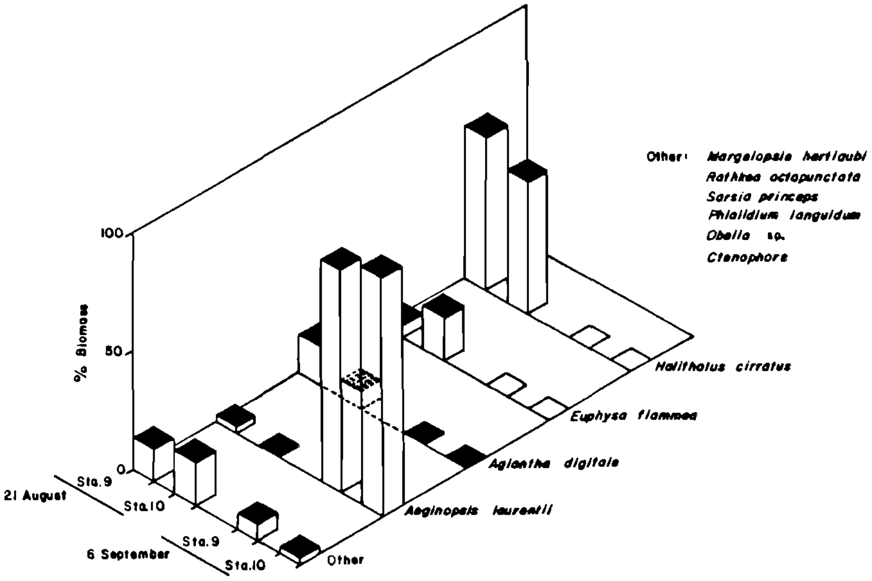


FIGURE 10. Percent composition of hydrozoan biomass collected in vertical tows off King Point, Y.T., on 21 August and 6 September 1980. Each bar is based on six samples.

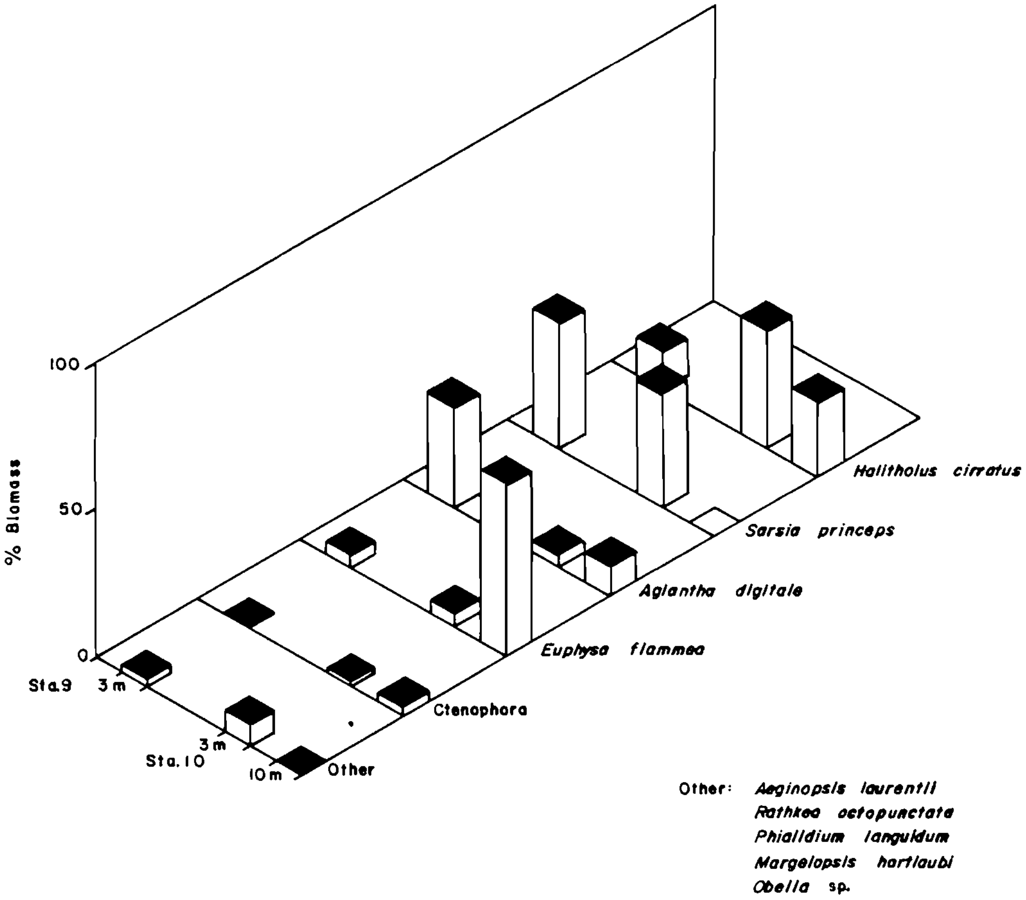


FIGURE 11. Percent composition of hydrozoan biomass collected in horizontal tows off King Point, Y.T., on 20 August 1980. Each bar is based on six samples.

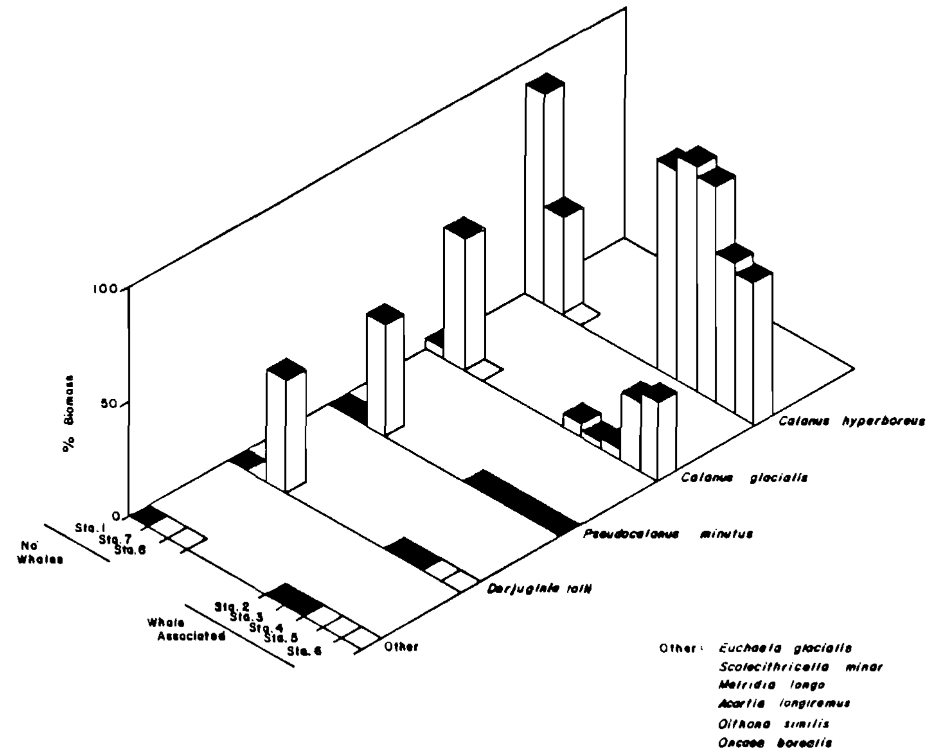


FIGURE 12. Percent composition of copepod biomass collected in vertical tows off Richards Island, N.W.T., 14-26 August 1980. Whales were present at stations 2-6 and were not seen at stations 1, 7, 8. Each bar is based on six samples.

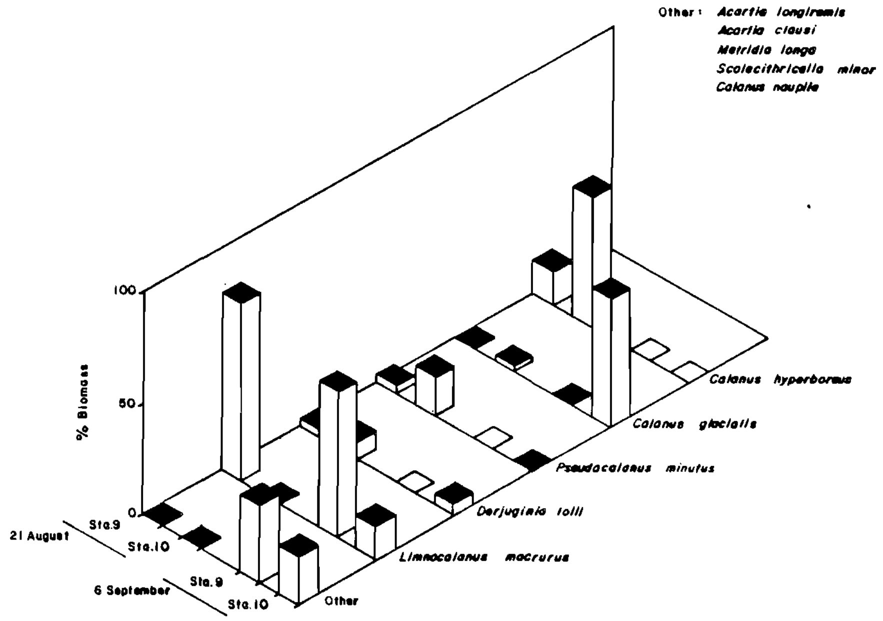


FIGURE 13. Percent composition of copepod biomass collected in vertical tows off King Point, Y.T., on 21 August and 6 September 1980. Each bar is based on six samples.

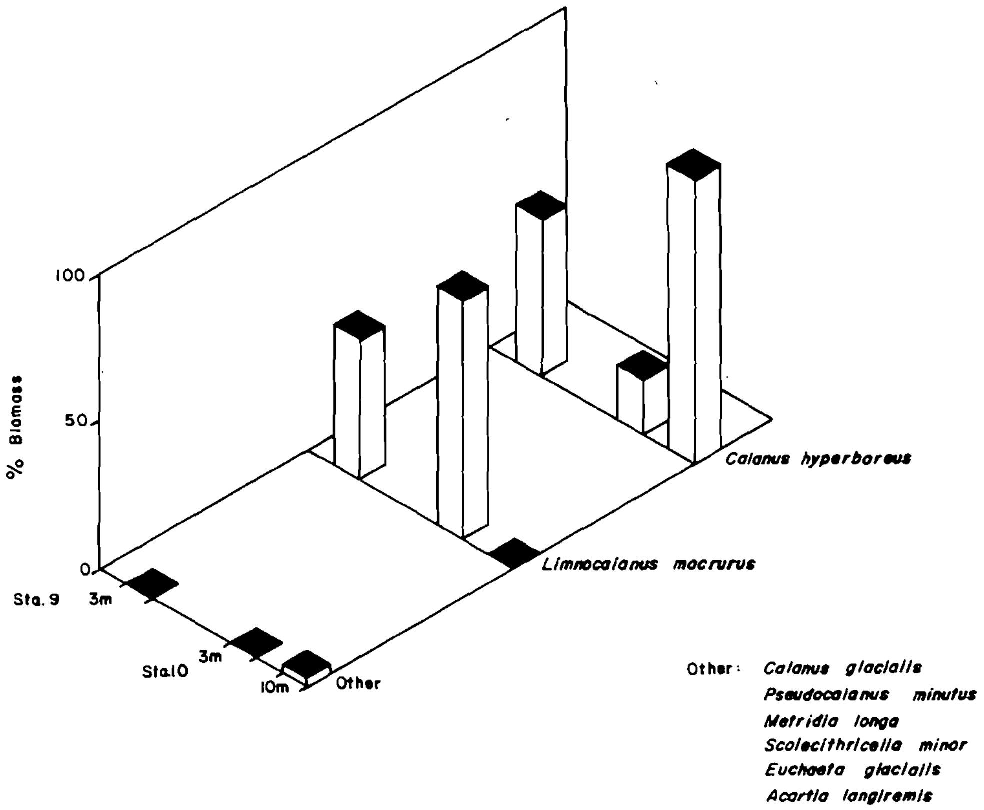


FIGURE 14. Percent composition of copepod biomass collected in horizontal tows off King Point, Y.T., on 20 August 1980. Each bar is based on six samples.

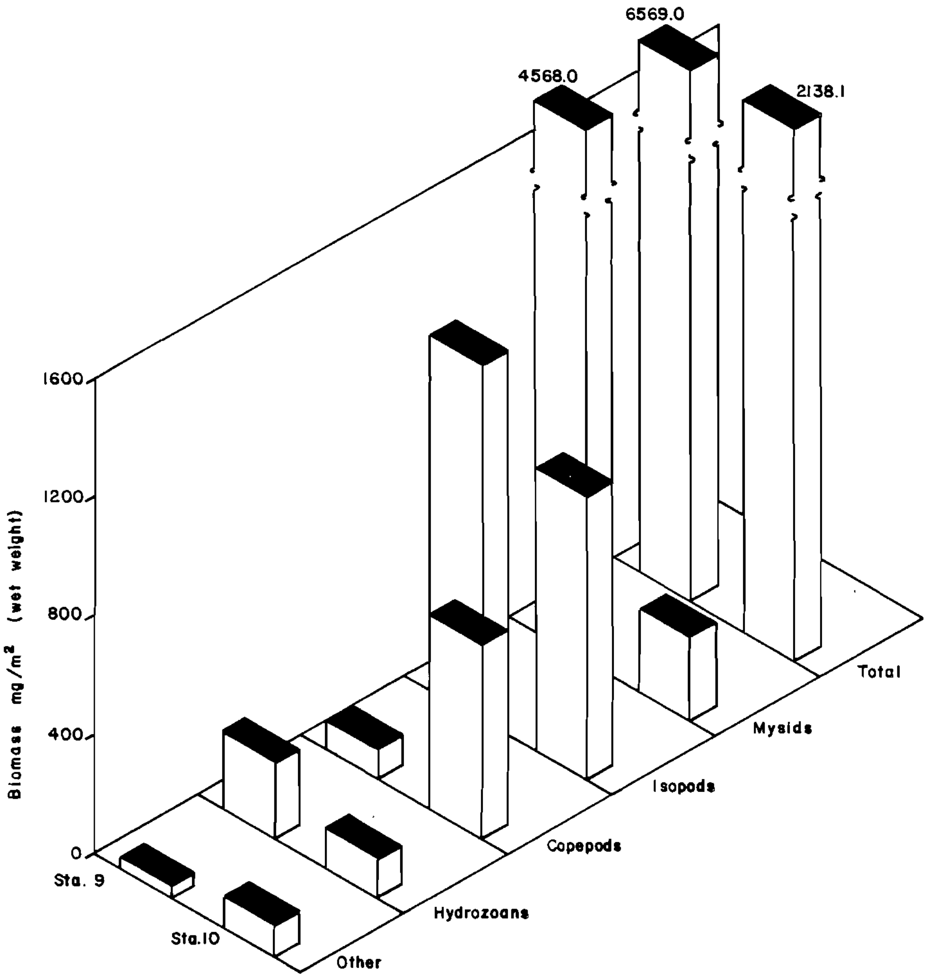


FIGURE 15. Biomass (mg/m^2 wet weight) of major groups of zooplankton and epibenthic invertebrates collected by drop nets at stations off King Point, Y.T., on 20 August 1980. Each bar is based on five samples (station 9) or three samples (station 10).

Zooplankton Results in 1981

Total zooplankton biomass (wet weight) during the 1981 field season ranged from 0.06 mg/m^3 at Station L-1 (0 m, 1 August) to 2456.00 mg/m^3 at Station N-11 (15 m, 24 August). In terms of total zooplankton biomass (all samples considered), the dominant zooplankters varied with depth. At the surface (0 m), copepods, ctenophores and hydrozoans accounted for 81%, 14% and 3% of the total biomass, respectively; at the 5 m depth, copepods (33%), hydrozoans (28%), ctenophores (7%) and young-of-the-year fish (3%) were the dominant groups; and at the 10 m depth (excluding the very near-bottom samples at Station N-13), hydrozoans (55%), copepods (31%), ctenophores (4%) and YOY fish (3%) were the major groups. The 15 m depth was most diverse in terms of biomass; there were six dominant groups, including copepods (54%), hydrozoans (20%), larvaceans (8%), mysids (5%), amphipods (4%) and ctenophores (3%). At the deepest depths sampled (20 and 30 m), copepods and hydrozoans were the most important groups in terms of biomass. Copepods contributed 66% and 87% to total zooplankton biomass at 20 and 30 m, respectively, while hydrozoans contributed 27% and 9%. Thus, as was the case with the vertical haul samples in 1980, copepods and hydrozoans comprised, by far, the greatest proportion of total zooplankton biomass.

The major species of copepods and hydrozoans that accounted for most of the biomass were the same in both years of the study (Appendix Tables 1 to 9).

Species Composition of Zooplankton, 1980-1981

The number of zooplankton species collected was greater in 1980 than in 1981 (70 species and 55 species, respectively; Table 3). This difference was probably attributable to a combination of two factors: (1) the wider variety of habitats sampled in 1980 than in 1981 (i.e. more nearshore and near-bottom samples in 1980), and (2) differences in sampling technique (i.e. vertical hauls in 1980 vs. horizontal tows in 1981). The two groups that generally dominated the zooplankton community, in terms of biomass, during both years--calanoid copepods and hydrozoans--also provided the highest numbers of species (Table 3). More species of amphipods were collected in 1981,

Table 3. Approximate numbers of species collected in the southern Beaufort Sea zooplankton samples during 1980 and 1981.

Major Group	Number of Species 1980	1981
Hydrozoa	11	12
Siphonophora	1	-
Gastropoda (benthic)	0	1
Ctenophora	2	2
Polychaeta	2	-
Nematoda	1	-
Oligochaeta	1	-
Pteropoda	2	2
Bivalvia	1	-
Isopoda	2	-
Cirripedia	1	1
Ostracoda	1	-
Cumacea	1	-
Cladocera	-	1
Cirripedia	1	1
Calanoida	15	12
Cyclopoida	3	-
Harpacticoida	3	-
Mysidacea	2	3
Decapoda	1	1
Chaetognatha	2	1
Larvacea	2	1
Amphipoda	8	10
Euphausiacea	1	1
Echinodermata	1	1
Pisces	5	5
	70	55

probably reflecting the larger net and higher towing speed in 1981 than in 1980.

Detailed species lists compiled from 1980 and 1981 samples are presented in Appendix Tables 1 to 9 and the major species and groups collected in 1981 are discussed in a following section ('Major Species and Groups').

Spatial Distribution of Zooplankton Biomass, 1981

The areal distribution and the abundance and biomass of zooplankton depend on factors such as wind, currents, temperature and salinity. Consequently, a high degree of temporal and geographic variability in zooplankton abundance and biomass can be expected. During the present study, samples were collected along a north-south transect (Stations N-1, L-1, N-7, N-6, N-5; Figure 2) during a relatively short time period (12 hours) on 11-12 August 1981 to assess the geographic distribution of zooplankton biomass in the area. The distribution of mean biomass of major zooplankton groups along this inshore to offshore transect is listed in Table 4, and shown in Figure 16. It is important to note that the water depth at stations along this transect increased, with distance from shore, from 14 m to 40 m. Typically, the highest biomasses were obtained at depths of 10 m or below and copepods increased in importance with both increasing depth and increasing distance from shore (Table 4; Fig. 16). It appears that the more saline deeper waters support a greater total zooplankton biomass than do the shallower brackish inshore waters. In all cases where comparisons are possible, the highest total zooplankton biomasses were found either at or below the thermocline (Table 5). It is likely that the density gradient (as represented by the strong thermocline and halocline) present during the summer in the Mackenzie Delta region acts as a barrier to zooplankton movement. In other areas of the world, strong density gradients have been reported to concentrate zooplankton (Pingree et al. 1974; Brown 1980; Herman et al. 1981; Owen 1981). It is likely that this also occurs in the southern Beaufort Sea. Our data (Table 5) and some of our echo sounding records strongly suggest that this commonly occurs in the region.

Table 4. Mean (±s.d.) biomass of major zooplankton groups along the oceanographic transect conducted 11-12 August 1981. N=3 for each depth sampled. Units are mg/m³ wet weight.

Group/Depth	Station N-1 14.0 m	Station L-1 20.0 m	Station N-7 27.0 m	Station N-6 32.0 m	Station N-5 40.0 m
Hydrozoa					
0	1.55 ± 1.38	0.68 ± 1.00	0.08 ± 0.11	0.00	0.00
5	1.38 ± 1.94	52.56 ± 40.24	-	-	-
10	-	145.51 ± 83.59	-	-	-
15	-	-	501.03 ± 107.98	44.09 ± 33.49	-
20	-	-	76.72 ± 11.79	104.43 ± 44.52	72.21 ± 29.22
30	-	-	-	-	29.65 ± 4.83
Ctenophora					
0	0.60 ± 0.78	0.36 ± 0.61	0.20 0.35	0.00	0.00
5	2.15 ± 1.95	0.44 ± 0.30	-	-	-
10	-	11.10 ± 3.93	-	-	-
15	-	-	1.21 ± 1.30	0.08 ± 0.01	-
20	-	-	22.55 ± 7.25	3.14 ± 1.85	9.15 ± 9.56
30	-	-	-	-	2.45 ± 1.06
Pteropoda					
0	0.00	0.00	0.00	<0.01	0.00
5	0.00	0.08 ± 0.07	-	-	-
10	-	2.15 ± 1.33	-	-	-
15	-	-	1.46 ± 1.03	<0.01	-
20	-	-	0.95 ± 0.46	0.20 ± 0.10	1.48 ± 0.07
30	-	-	-	-	0.83 ± 0.62
Calanoida					
0	0.85 ± 0.40	1.85 ± 1.59	0.94 ± 0.13	3.13 ± 5.12	0.45 ± 0.15
5	3.54 ± 2.24	6.89 ± 4.91	-	-	-
10	-	106.72 ± 77.23	-	-	-
15	-	-	55.00 ± 66.64	22.66 ± 18.52	-
20	-	-	142.59 ± 82.64	94.31 ± 60.62	394.87 ± 273.16
30	-	-	-	-	274.00 ± 174.40
Mysidacea					
0	0.00	0.00	0.00	0.00	0.00
5	0.00	0.00	-	-	-
10	-	6.01 ± 8.75	-	-	-
15	-	-	0.00	0.00	-
20	-	-	0.21 ± 0.06	0.00	0.13 ± 0.11
30	-	-	-	-	0.58 ± 0.41
Euphausiacea					
0	0.00	0.00	0.00	0.25 ± 0.43	0.00
5	0.00	0.01 ± 0.02	-	-	-
10	-	5.79 ± 3.10	-	-	-
15	-	-	0.00	0.00	-
20	-	-	4.32 ± 0.69	0.00	0.01 ± 0.01
30	-	-	-	-	1.92 ± 2.53
Amphipoda					
0	0.00	0.00	<0.01	0.06 ± 0.10	<0.01
5	0.00	0.03 ± 0.04	-	-	-
10	-	1.61 ± 0.94	-	-	-
15	-	-	3.61 ± 1.68	0.06 ± 0.06	-
20	-	-	0.09 ± 0.09	0.76 ± 0.72	0.80 ± 0.14
30	-	-	-	-	2.54 ± 1.32
Decapoda					
0	0.00	0.00	0.00	0.00	0.00
5	0.00	0.01 ± 0.01	-	-	-
10	-	1.56 ± 0.92	-	-	-
15	-	-	3.02 ± 1.81	0.07 ± 0.11	-
20	-	-	0.25 ± 0.11	1.02 ± 0.62	1.14 ± 0.50
30	-	-	-	-	0.67 ± 0.50
Chaetognatha					
0	0.00	0.00	0.00	0.02 0.03	0.00
5	0.00	0.13 ± 0.13	-	-	-
10	-	7.16 ± 5.43	-	-	-
15	-	-	4.88 ± 2.97	0.17 ± 0.27	-
20	-	-	4.80 ± 1.07	0.67 ± 0.47	1.32 ± 0.54
30	-	-	-	-	1.86 ± 1.02

Table 4. (Cont'd.)

Group/Depth	Station N-1 14.0 m	Station L-1 20.0 m	Station N-7 27.0 m	Station N-6 32.0 m	Station N-5 40.0 m
Pisces					
0	0.00	0.00	0.12 ± 0.21	0.00	0.00
5	0.00	0.00	-	-	-
10	-	6.63 ± 4.18	-	-	-
15	-	-	4.54 ± 1.05	0.56 ± 0.83	-
20	-	-	0.00	4.75 ± 4.88	3.54 ± 1.56
30	-	-	-	-	0.08 ± 0.13
TOTAL					
0	4.23 ± 1.89	3.46 ± 3.86	1.88 ± 0.75	4.04 ± 5.96	0.48 ± 0.16
5	7.72 ± 5.84	60.18 ± 45.08	-	-	-
10	-	294.23 ± 41.04	-	-	-
15	-	-	580.97 ± 92.76	67.76 ± 52.01	-
20	-	-	255.83 ± 92.56	209.73 ± 107.97	485.30 ± 266.55
30	-	-	-	-	315.40 ± 170.97

-Means no data.

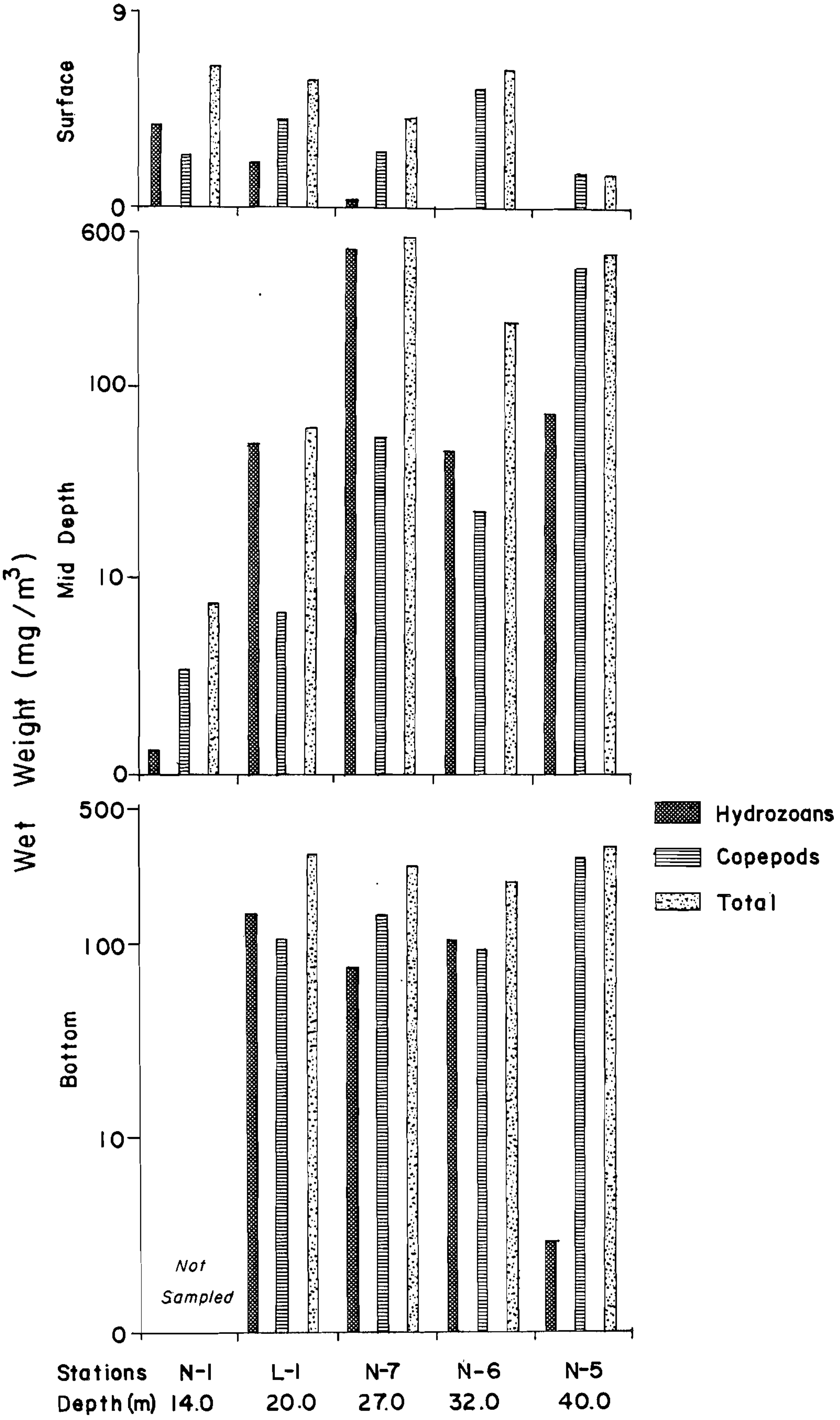


FIGURE 16. Biomass (wet weight, mg/m^3) in relation to depth along an oceanographic transect, 11-12 August 1981. For actual depths sampled see Table 4. Note that scale is logarithmic.

Table 5. Comparison of thermocline depth with depth of highest mean zooplankton biomass. Only those stations where sampling was conducted above and below the thermocline are included.

Station	Date	Depth of Thermocline (m)	Depth of Highest Biomass (m)	Depths Sampled (m)
N-1	31 July	5-7.5	10	0, 5, 10
L-1	01 August	5-7.5	15	0, 5, 15
N-5	11 August	10-15	20	0, 10, 20, 30
N-6	11 August	5-15	20	0, 15, 20
N-7	11 August	7.5-15	15	0, 15, 20
L-1	11 August	7.5-10	10	0, 5, 10
*N-9	18 August	10-15	15	0, 2, 15
*N-10	19 August	10-15	15	0, 5, 15
*N-11	24 August	10-15	15	0, 5, 15
N-12	24 August	not clear	15	0, 5, 15
L-1	06 September	none	5	0, 5, 15

*Whales present; thermocline present but not pronounced.

Temporal Distribution of Zooplankton Biomass, 1981

In the present study, temporal changes in the total zooplankton community structure and biomass were assessed using the data from Station L-1, which was sampled on 3 occasions (1 August, 11 August and 6 September 1981; Fig. 17). Mean zooplankton biomass at the 0 m depth was always low but showed slight increases as the season progressed. At 5 m, the total biomass increased sharply from 1 August to 11 August and was even higher on 6 September. The highest biomasses occurred at or below the 10 m sampling depth during the first two sampling periods; at that depth there was a slight decrease in the 6 September sample (Fig. 17). The highest total biomasses were below the thermo- and halocline (7.5-10 m depth) on 1 and 11 August, but by 6 September this strong density gradient had broken down, possibly accounting for the reduced total biomass found at the deeper depths (15 m) at this time.

On 1 August, the zooplankton was dominated by larvaceans (62%, 54%, and 19% of biomass at 0, 5 and 15 m, respectively) and young-of-the-year (YOY) fish (primarily gadids, 6%, 24% and 24%). On 11 August, after several days of high winds, the zooplankton at this station was dominated by hydrozoans (20%, 87% and 50% at 0, 5 and 10 m, respectively) and calanoid copepods (53%, 12% and 36%); larvaceans had disappeared entirely. By 6 September, larvaceans again dominated the zooplankton biomass (21%, 54%, 63% at 0, 5 and 15 m) with hydrozoans (53%, 13%, 17%) and calanoid copepods (20%, 28%, 1%) also contributing significant amounts to total zooplankton biomass.

The total number of zooplankton species found in the upper 15 m of water at Station L-1 was approximately the same (39) during the two August sampling dates, but had declined to approximately 31 by 6 September. Volumes filtered were comparable on each date.

Echo Sounding Records, 1981

Hydroacoustic observations using a high frequency echo sounder were obtained routinely during zooplankton tows, and while steaming to and from oceanographic stations and whale feeding areas. Because the vessel was also involved in a variety of disturbance studies (Fraker et al. 1982), it

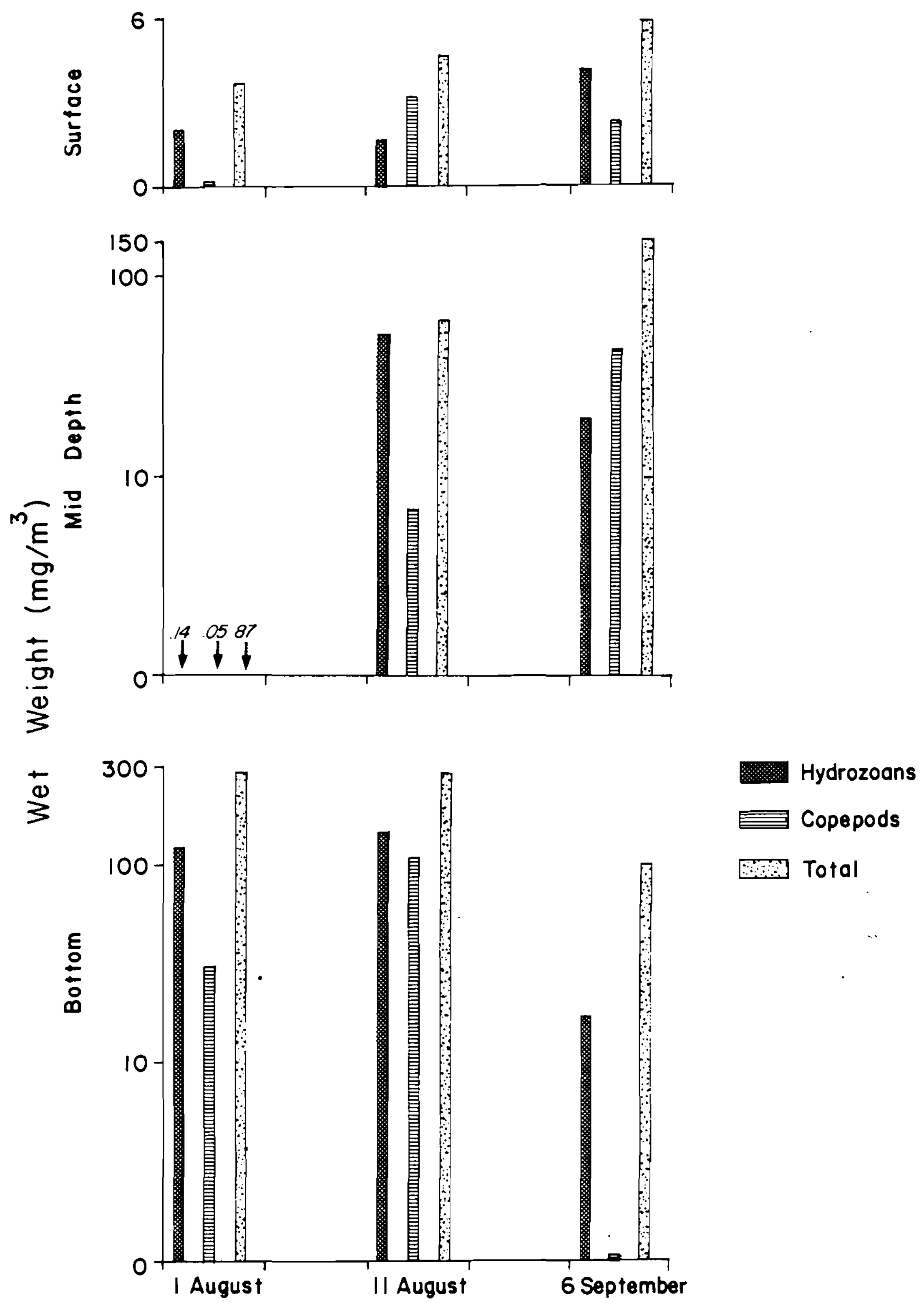


FIGURE 17. Mean biomass (wet weight mg/m^3) of zooplankton in relation to depth and date at Station L-1, 1981. Samples were collected on 1 and 11 August 1981 and on 6 September 1981. Note that the scale is logarithmic. N = 3 for each depth-date combination.

was not possible to conduct systematic grid surveys. Such surveys would have allowed a rough mapping of zooplankton concentrations and an approximate determination of the densities of zooplankters in the aggregations. However, the echo sounder did record several features of relevance to bowhead whale feeding during the study. The distinct layer at 5 m depth on echo sounding records early in the season (Fig. 5) was caused by a sharp density gradient. At this time, the layer was a dominant feature in nearshore waters (at least as far offshore as Station L-1). The associated thermocline possibly created a barrier to the upward movement of marine zooplankton and may have been responsible for the higher zooplankton biomass observed at or below the 5 m depth in most collections. These distinct layers had broken down and ceased to be a dominant feature after approximately 11 August 1981.

In addition to these layers observed early in the season, patches of zooplankton (varying in size from several to several hundred metres across) were observed periodically. These patches appeared to be randomly distributed in the study area and did not appear to be associated with the few meandering 'fronts' that were observed at the surface.

In an area where whales were observed feeding (Station N-9; 18 August), hydroacoustic observations and net samples showed that relatively dense concentrations of zooplankton were present. The concentrations appeared to be more or less uniformly distributed from 1 to 4 m depths at a time when bowheads feeding just below the surface were observed from the aircraft (Fig. 18). This record was obtained while the vessel was sampling zooplankton at 0, 2 and 15 m depths; whales were feeding in the immediate vicinity and in several instances approached to within 20 m of the boat.

Relatively dense zooplankton concentrations were again observed in the immediate vicinity of whales feeding in the water column at Station N-11 on 24 August. At this time, the zooplankton concentrations again appeared to be more or less evenly distributed between 1 and 4 m depths (Fig. 19). The trace shown in Figure 19 is a portion of a much longer trace (total running time of 2 h and 22 min) that was obtained while the vessel was observing whales and conducting horizontal zooplankton tows at 0, 5 and 15 m depths. In several instances, the echoes became much fainter than those shown in Figure 19 and almost disappeared. The zooplankton samples that were

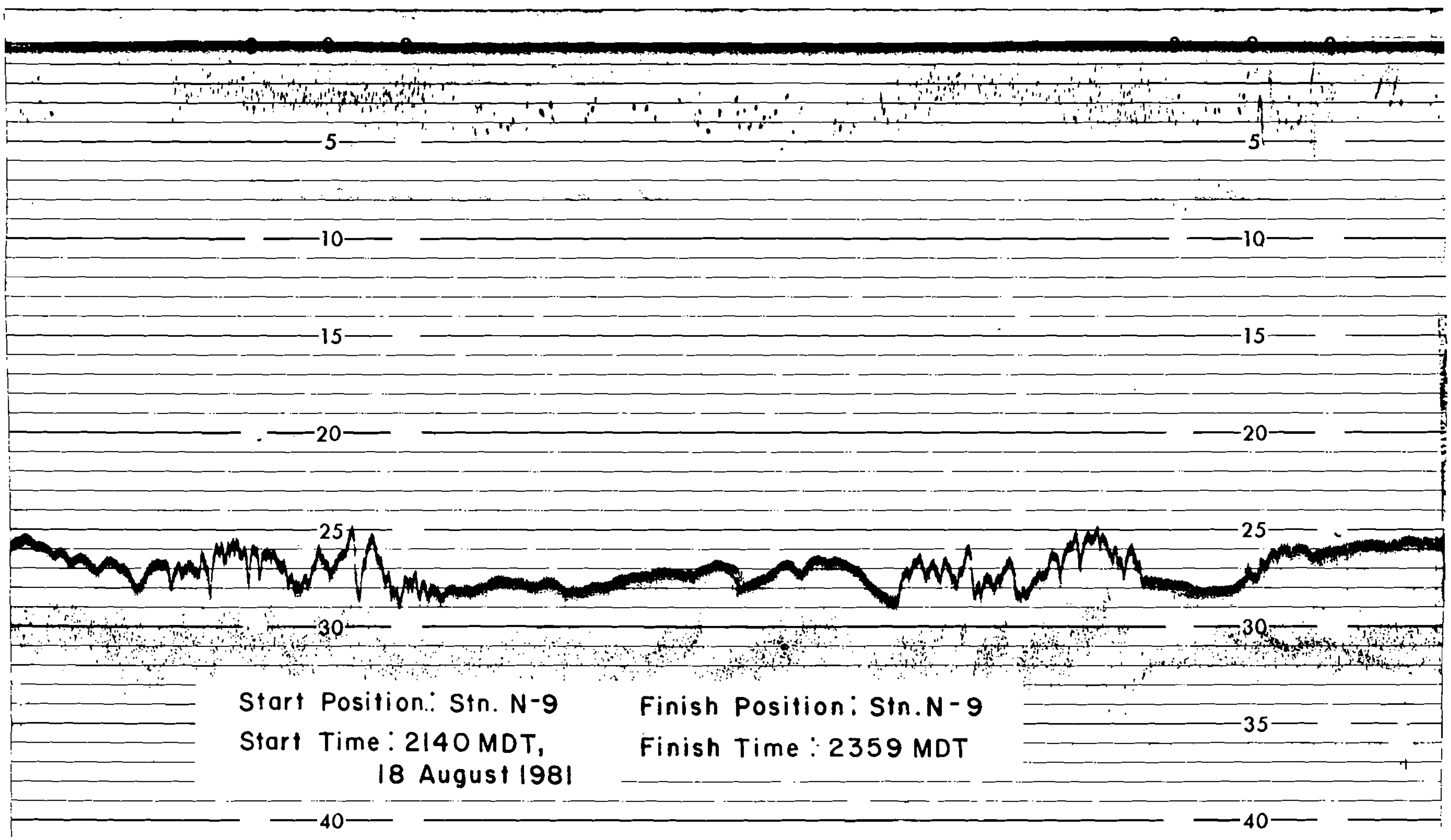


FIGURE 18. Echosounder trace obtained among feeding whales at Station N-9 on 18 August 1981. Echoes show moderate concentrations of zooplankton at 1-4 m depths.

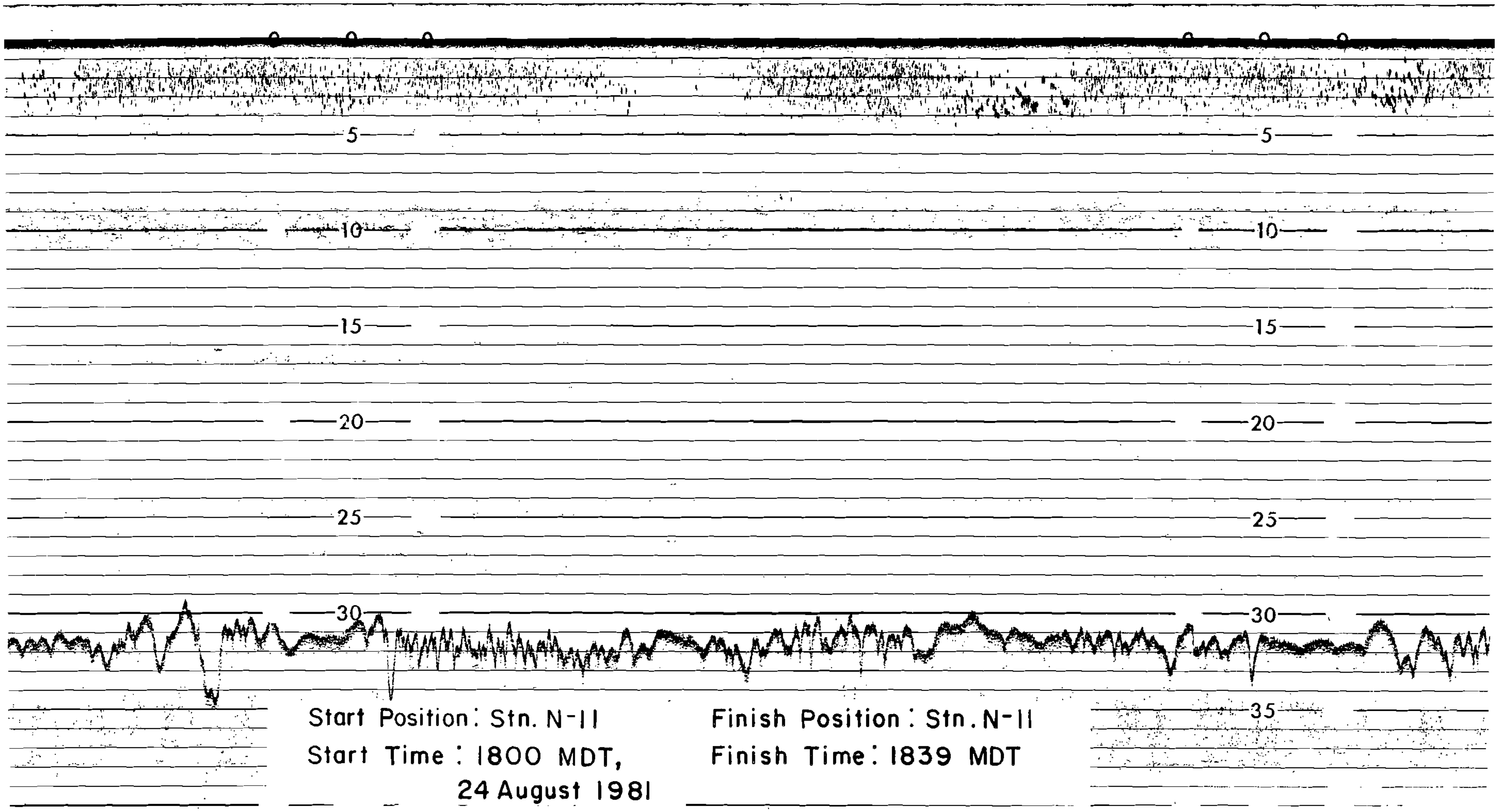


FIGURE 19. Echosounder trace showing plankton concentrations at 1-4 m depths. Sounding was conducted at Station N-11 on 24 August 1981 in the presence of whales. Strongest echoes appeared to be caused by YOY gadids (based on zooplankton tows conducted at the same time).

collected at the times of light echoes contained few YOY arctic cod as compared to those samples collected when hydroacoustic observations indicated dense concentrations of zooplankton. We suspect that YOY arctic cod were responsible for the most distinctive echoes in Figure 19. Previously, both gadids and pteropods (with pteropods congregating at density interfaces between water masses) have been reported by Hansen and Dunbar (1970) as causing sound 'scattering layers' in the Arctic Ocean. Both YOY gadids and pteropods were present at the whale feeding stations.

In contrast to the occurrence of observable dense zooplankton concentrations at Station N-11 in the whale feeding area, a lower zooplankton biomass was found on the same date at Station N-12, where no whales were observed. Station N-12 was sampled on 24 August shortly after the echo records and net samples were collected in the whale feeding area (Station N-11). At Station N-12, zooplankton biomasses were lower and the echo traces did not show zooplankton concentrations of any type (Figure 20). This trace showed only a few scattered targets, possibly attributable to individual animals including one recognizable fish.

Major Species and Groups

Copepods

Copepods are an important constituent in the diets of right and bowhead whales (Nemoto 1970; Mitchell 1975; Marquette 1977; Lowry and Burns 1980). Stomach analysis of bowhead whales taken in the Alaskan Beaufort Sea has shown that copepods and euphausiids were by far the most common food items (Lowry et al. 1978; Lowry and Burns 1980). Lowry and Burns (1980) reported that the copepod *Calanus hyperboreus* was the dominant food item in stomachs from 3 of the 5 bowhead whales landed at Kaktovik, Alaska, in September - October 1979. Other species of copepods (mostly *C. glacialis* and *Metridia longa*) were found in a bowhead taken at Barrow on 5 May 1977 (Marquette 1979).

Because of their widespread distribution, copepods were collected at every station during both years of the present study (Appendix Tables 1-9; Figures 12-14).

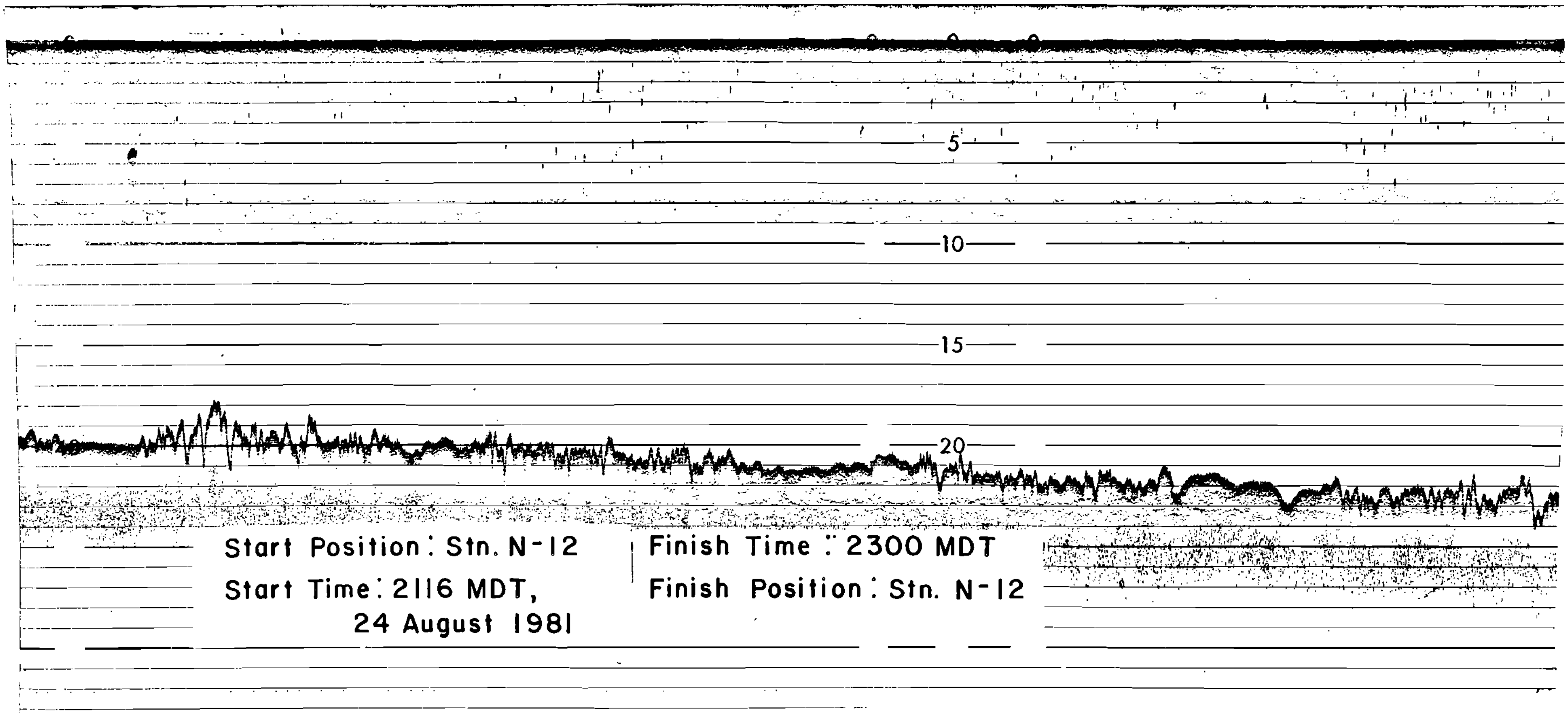


FIGURE 20. Echosounder trace showing the virtual absence of recordable zooplankton at Station N-12 on 24 August 1981. Recording was conducted in the absence of observable whales.

Calanus hyperboreus.--This species, the largest of the arctic copepods, is distributed throughout the Arctic Ocean (Brodskii 1950). Sekerak et al. (1979) provide a detailed description of its life history in arctic waters with special emphasis on eastern Lancaster Sound and northwest Baffin Bay. In the southern Beaufort Sea, *C. hyperboreus* occurs over most of the region and comprises a major element of the copepod community (Grainger 1965, 1975). In both 1980 and 1981 of this study, *C. hyperboreus* was generally the dominant species of copepod in terms of biomass, although other species or groups of species comprised a larger portion of the copepod biomass at certain individual stations (1980 Figs. 12 to 14; 1981 Appendix Tables 7 to 9). The 1981 results also suggested that the biomass of *C. hyperboreus* increased with depth and that the highest biomass occurred below the thermocline (Appendix Tables 7 to 9).

Calanus glacialis.--This species is widely distributed throughout the Arctic Basin and Canadian Arctic Archipelago (Grainger 1965, 1975; Mohammed and Grainger 1974; Sekerak et al. 1976, 1979). Sekerak et al. (1979) review its life history. *C. glacialis* (copepodite IV and V) forms a major component of the copepod communities in the southeastern Beaufort Sea (Grainger 1965, 1975). In both years of the present study, *C. glacialis* was the second most important copepod in terms of biomass (1980 Figs. 12 to 14; 1981 Appendix Tables 7 to 9). In 1981, *C. glacialis* did not show the same increase in biomass with increased depth as did *C. hyperboreus*, although the highest biomass estimates occurred below the thermocline (Appendix Tables 7 to 9).

Limnocalanus macrurus grimaldi.--This subspecies has been reported almost exclusively (north of the Atlantic) from near-surface waters of the marginal seas of the Arctic Ocean (Grainger 1965). In the southeastern Beaufort Sea it is abundant wherever water of low salinity occurs (Grainger 1975; Grainger and Grohe 1975). Johnson (1956) found this species to have estuarine affinities, and its presence may indicate the spread of river water out over the ocean. *L. macrurus grimaldi* was not found at any of the eight stations sampled off Richards Island, N.W.T., in 1980; however, *L. macrurus grimaldi* (adult males and females and copepodite V) formed a major component of the copepod communities at both King Point stations in 1980 (Figs. 12-14). The apparent absence of this species off Richards Island in 1980 is not readily explainable as the temperature and salinity characteristics of the water masses in this area and off King Point were essentially the same (Fig. 2). In 1981 this species was common in collections off Richards Island. However, it was not the main contributor to the copepod biomass at any of the stations (Appendix Tables 7 to 9) where zooplankton was identified to species. Insufficient numbers of this species were collected in 1981 to allow a meaningful interpretation of the relationship between depth and biomass.

Pseudocalanus minutus.--The arctic distribution of *Pseudocalanus minutus* is summarized by Shih et al. (1971). In terms of numbers, *P. minutus* is one of the most abundant copepods in arctic waters (Grainger 1965). Its life history is summarized in Sekerak et al. (1979). Grainger (1975) found *P. minutus* to be widely distributed in the southeastern Beaufort Sea. In both 1980 and 1981, although present at most stations, it contributed significantly to the copepod biomass at only a very few stations (1980: Figs. 12-14; 1981: Appendix Tables 7 to 9). The *P. minutus* collected were mostly adult males and females and copepodite V individuals. The 1981 samples provide no evidence of a relationship between depth and biomass for this species (Appendix Tables 7 to 9).

Derjuginia tolli.--Shih et al. (1971) summarize the arctic distribution of *Derjuginia tolli*. Grainger (1965, 1975) found it to be widely distributed in the southeastern Beaufort Sea between Herschel Island and Cape Dalhousie. It is found almost exclusively (north of the Atlantic and Pacific Oceans) in near-surface waters of the marginal seas of the Arctic Ocean (Grainger 1965). In 1980, *D. tolli* (copepodite IV and V) was found at approximately half of the stations sampled, but only at Station 8 did it contribute significantly to the copepod biomass (Figs. 12-14). In 1981, *D. tolli* did not comprise a dominant portion of the copepod biomass at any station or depth. It was typically absent from surface waters and its highest biomass estimates occurred in samples collected near the bottom (Appendix Tables 7 to 9).

Hydrozoans and Ctenophores

In this analysis, hydrozoans and ctenophores (i.e. jellyfish and comb jellies) have been treated as a single group. Both are extremely fragile and frequently suffer damage during collection. Estimates of their biomass should be interpreted with these limitations in mind. Despite this, at almost every station and depth sampled in 1980, hydrozoans and ctenophores comprised the dominant portion of the biomass (Figs. 9-11, Appendix Tables 1-6). In 1981, this group comprised a major portion of the biomass at all stations and depths; however, at some station-depth combinations it was second to copepods or other groups in importance (Appendix Tables 7 to 9).

Although these abundant organisms have not been reported in bowhead stomach samples, this absence may be artifactual. In a study of bird feeding ecology in an arctic lagoon, birds (another warm blooded group) were observed feeding on hydrozoans but no evidence of these organisms was found when the stomach contents were analyzed (Johnson and Richardson 1981:337). Bowheads must ingest large quantities of these abundant organisms while feeding. The apparent absence of hydrozoans from the stomach contents may be due to their fragile nature (i.e. no identifiable structure is left by the time they enter the stomach), to the length of time between feeding and the death of the whale, and possibly to continued digestion after death (although the digestive process may be arrested by death--Brodie et al. 1978). In a living whale 25-30% of the stomach contents are digested within 5 h even when less fragile foods are considered (Brodie et al. 1978). It should be noted that hydrozoans are also common in the Alaskan Beaufort Sea; they are the second most abundant group after copepods (Horner 1979).

The biomasses of hydrozoans and ctenophores collected in the water column in both vertical and horizontal tows during the present study are shown in Appendix Tables 1-5 and Figures 9-11. Five species of hydrozoan (Halitholus cirratus, Euphysa flammea, Sarsia princeps, Aglantha digitale, Aeginopsis laurentii) accounted for most of the biomass of this group. Although they did not contribute significantly to the total hydrozoan biomass, several other species were present in the study area. Those identified in this study were Rathkea octopunctata, Phialidium languidum, Margelopsis hartlaubi, and Obelia sp. A brief description of each of the five major species follows.

Halitholus cirratus.--In the North American Arctic, Halitholus cirratus has been documented as occurring from Point Barrow, Alaska, east to Frobisher Bay, N.W.T. (MacGinitie 1955; Dunbar 1942). Kramp (1942) frequently found

H. cirratus in inshore waters of SW Greenland but only once in northern Baffin Bay. In NW Baffin Bay this species was found at only two inshore stations (Sekerak et al. 1979). However, in a more intensive sampling of surface water (0-150 m) in Lancaster Sound, H. cirratus was recorded at all stations (Sekerak et al. 1976). Grainger (1965) classifies this species as being primarily coastal and restricted in the southern Beaufort Sea to nearshore and shallow waters. In the 1980 vertical haul samples, H. cirratus (approximately 20-30 mm in diameter) comprised a significant portion of the hydrozoan biomass at all stations other than Stations 9 and 10 at King Point on 6 September, and in most cases it was the dominant species (Figs. 6-8). In 1981, H. cirratus comprised a significant portion of the hydrozoan biomass at all stations where the zooplankton was identified to species. In most cases the biomass of this species increased with depth and was highest below the thermocline (Appendix Tables 7 to 9). Nonetheless, the dominance of H. cirratus may be related to the presence of brackish water in this region as this species is known to have a limited tolerance of high salinities (Grainger 1965).

Euphysa flammea.--This species has been collected near Point Barrow, Alaska (MacGinitie 1955; Redburn 1974), in the southern Beaufort Sea (Grainger 1965, 1975), in Foxe Basin, N.W.T. (Grainger 1959), and off eastern Baffin Island (Kramp 1942). This species was not found in Lancaster Sound or NW Baffin Bay (Sekerak et al. 1976, 1979), possibly because of the deep waters in these areas; it appears to prefer nearshore shallow waters (Grainger 1965). In 1980, E. flammea (7-10 mm in diameter) was, in terms of biomass, the second most important hydrozoan after H. cirratus (Figs. 9-11). Only at King Point Stations 9 and 10 on 6 September was it not found. The results of the horizontal tows in 1981 showed E. flammea to be present at all stations; however, it was not a major component of the hydrozoan biomass at any station. Biomass of E. flammea showed no consistent relationship with depth. At Station L-1, it was absent from surface waters on 1 August, it was represented at all depths sampled on 11 August, and it was absent from the mid-depth and bottom samples on 6 September (Appendix Tables 7 to 9).

Sarsia princeps.--This species has been recorded from Point Barrow, Alaska (MacGinitie 1955), east to East Baffin Island (Kramp 1942). In the southern Beaufort Sea it has been characterized as a coastal species, restricted mainly to nearshore shallow waters (Grainger 1965). Although present at most stations in 1980, *S. princeps* (20-30 mm in diameter) comprised a significant portion of the hydrozoan biomass only in horizontal tows at depth 3 m at King Point Stations 9 and 10 (Figs. 9-11). In 1981, this species occurred only periodically in the samples and did not comprise a significant portion of the hydrozoan biomass at any station-depth combination (Appendix Tables 7 to 9).

Aglantha digitale.--This species is listed by Grainger (1965) as one of the most common arctic zooplankters. A summary of its arctic distribution (Point Barrow, southern Beaufort Sea, Jones Sound, Ellesmere Island, Foxe Basin) has been provided by Shih et al. (1971). *A. digitale* was the most common hydrozoan found in Lancaster Sound and NW Baffin Bay (Sekerak et al. 1976, 1979). In vertical haul samples collected in 1980 it was present at almost all stations, but it did not comprise a significant portion of the hydrozoan biomass at any of the stations (Figs. 9-11). In 1981, horizontal tows showed *A. digitale* to be present at all stations but not at all depths (Appendix Tables 7 to 9); as in 1980, this species did not comprise a significant portion of the hydrozoan biomass. The low abundance of *A. digitale* (20-30 mm in diameter) in this study may be due to the shallowness of the water. According to Grainger (1965), although this species extended well into the shallow waters of the southeastern Beaufort Sea, it was most abundant in offshore waters.

Aeginopsis laurentii.--The arctic distribution of *Aeginopsis laurentii* is the same as that reported for *Aglantha digitale* (Shih et al. 1971). Grainger (1965) reported *A. laurentii* in both inshore and offshore regions of the western Canadian Arctic. In 1980, *A. laurentii* (15-20 mm in diameter) was collected at almost every station, but comprised an insignificant portion of the hydrozoan biomass (Figs. 9-11). In 1981, it was also present in low numbers at every station; however, its biomass was greatest in samples collected just above the bottom (Appendix Tables 7 to 9).

Amphipods

Amphipods have been reported in the diets of five bowhead whales taken near Kaktovik, Alaska; however, in none of the whales did they form a major part of the stomach contents (Lowry and Burns 1980). In 1980, amphipods comprised only an incidental portion of the zooplankton biomass in the vertical haul samples. In 1981, although never a major component of the horizontal tow samples, 10 species of amphipods were collected. Four of the most important species are briefly discussed below.

Onisimus glacialis.--The distribution of Onisimus glacialis is circumpolar subarctic to arctic. It ranges south as far as Kotzebue, Alaska, and the Strait of Belle Isle in North America, and occurs off Iceland, Northern Norway, and the Russian Bering Sea in Europe and Asia (Shoemaker 1955; Holmquist 1965). In the Beaufort Sea O. glacialis inhabits the nearshore, brackish water zone; in deeper offshore waters it is replaced by O. litoralis and Boeckosimus affinis (Dunbar 1954; Feder and Schamel 1976; Griffiths and Dillinger 1981). Griffiths and Dillinger (1981) provide a detailed account of the life history of O. glacialis in the nearshore waters of the Beaufort Sea. In 1981 O. glacialis was collected only in near-bottom samples, and rarely did it contribute significantly to the amphipod biomass (Appendix Tables 7 to 9).

Apherusa glacialis.--This pelagic amphipod is circumpolar, arctic-subarctic; it usually occurs in the upper portions of the water column (Dunbar 1957) and on the under-ice surface (Barnard 1959; Buchanan et al. 1977; Thomson et al. 1978). It is considered to be a member of the ice-associated amphipod community in the Alaskan and Soviet Arctic and the Canadian High Arctic (Golikov and Averincev 1977; Divoky 1978; Cross 1982). During summer it occurs in large numbers on the undersurface of ice pans, but it also occurs in the water column in nearshore and offshore areas (Shoemaker 1955). Sekerak et al. (1979) sampled the entire water column in northwest Baffin Bay during summer and found that A. glacialis occurred at all depths (surface to >1200 m), but was most abundant between 250 and 1200 m. In 1981, A. glacialis was collected at most of the depths sampled; it showed a trend toward low biomass in surface waters and increasing biomass with depth (Appendix Tables 7 to 9).

Parathemisto libellula.--In the Arctic this species is circumpolar in distribution; it is found in the Pacific Ocean and in the Bering and Okhotsk seas as well. Parathemisto libellula is the largest member of the genus (up to 60 mm long) and is found in waters as deep as 2500 m (Shoemaker 1955). It has a two-year life-cycle in arctic waters and spawns from September to May or June (Dunbar 1957). The young are brooded in the female's marsupium. Broods are released in early May. Juveniles initially live in the surface 50 m, but by late June (at a size of 10 mm) they migrate vertically. By late October, they have a daytime depth of 200-300 m. Males mature in the late winter at 19-21 mm and females at 21-25 mm (Wing 1976). The species is predominantly carnivorous but also ingests some vegetable matter (Dunbar 1946). In 1981, _P. libellula_ was collected at all stations; it tended to be absent from surface waters and its biomass appeared to increase with depth (Appendix Tables 7 to 9).

Parathemisto abyssorum.--This arctic species also occurs in deep waters of subarctic regions (Ekman 1953). Bowman (1960) found that _P. abyssorum_ avoided shallow coastal waters and was generally found throughout the water column over deep areas. In Lancaster Sound, N.W.T., during the summer of 1976, this species was more abundant in deeper water (150 m) than in shallow water (<50 m) (Sekerak et al. 1976). However, Sekerak et al. (1979) found that this species was most abundant in the top 150 m of the water column in the Baffin Bay area. In the Barents Sea, _P. abyssorum_ requires two years to reach maturity, breeds once, and then dies (Bogorov 1940, in Bowman 1960). The breeding season in the arctic extends from February to August (Bowman 1960). _Parathemisto abyssorum_ was commonly collected at all stations in 1981; however, only on a few occasions and at particular depths did it form a major portion of the amphipod biomass (Appendix Tables 7 to 9).

Mysids and Euphausiids

Mysids (_Mysis litoralis_) and euphausiids (_Thysanoessa raschii_) appear to be important food items in the diets of bowhead whales in the Alaskan Beaufort Sea (Lowry et al. 1978; Lowry and Burns 1980). In sampled portions of the present study area during the two years of the study, only one species of mysid (_Mysis litoralis_) was common while _Mysis relicta_ and euphausiids (_Thysanoessa_ sp.) were rare.

In 1980, mysids were widespread throughout the study area but the numbers and biomasses collected from the water column were low, and mysids generally did not contribute significantly to the total biomass of zooplankton (Appendix Tables 1-5). However, the results of horizontal tows taken at King Point Stations 9 and 10 showed mysids to be locally abundant and that they can comprise the major portion of the zooplankton biomass at a given depth (Fig. 8). Horizontal tow samples collected in 1981 showed a somewhat similar pattern in that mysids were widespread in the area but tended to occur in aggregations at specific depths. For example, at certain 1981 stations north of Richards Island mysids were abundant in samples collected at the deepest depths (15 m at N-9 on 18/19 August; 10 m at L-1 on 11 August; 15 m at N-12 on 24 August) and were absent from the other depths sampled.

There are also some previous observations of swarms of mysids in the water column in the arctic (Thomson et al. 1978; Griffiths and Dillinger 1981). The bowheads that contain substantial quantities of mysids (Lowry and Burns 1980) may have fed in areas with such swarms or they may have taken mysids near the bottom (see below).

Biomass Near the Bottom

Epibenthos

The contents of drop net samples collected at King Point Stations 9 and 10 in 1980 and at Station N-4 (off the Tuktoyaktuk Peninsula) in 1981 are shown in Appendix Table 6 and Figure 15. These nets collect epibenthic animals (i.e. those found on and within 1 m above the bottom). Infaunal organisms found in these samples are not included in the results since this technique does not sample infauna quantitatively.

In 1980, mysids, isopods and to a lesser extent copepods and hydrozoans accounted for the major portion of the biomass near the bottom (Fig. 15). The copepod and hydrozoan species found near the bottom were the same as those collected in the water column with vertical and horizontal tows (see above). A volumetric comparison (on the 1980 data) of biomasses near the bottom and in the water column at the King Point stations shows that at the shallow station (9) the bottom biomass (epibenthos plus bottom metre of water column) was substantially higher than water-column biomass (1.31 vs. 0.20 g/m^3), while at the deeper station (10) the biomasses were about equal (0.42

vs. 0.43 g/m^3). However, if we consider the total biomass in the water column on a (g/m^2) basis, then the results are reversed; the near-bottom biomass and total water-column biomass are approximately equal at Station 9 (depth 5.5 m; 1.31 vs. 1.10 g/m^2), while at Station 10 the water-column biomass greatly exceeds the near-bottom biomass (depth 20.0 m; 0.42 vs. 8.60 g/m^2). This is attributable to the low near-bottom biomass and the much greater depth at Station 10. In summary, the limited number of samples from King Point, Y.T., suggest that total water-column biomass is about as high as (in very shallow water) or higher than (in deeper water) near-bottom biomass. However, the biomass per unit volume near the bottom is higher (in shallow water) or at least as high (in deeper water) as the biomass per unit volume in the water column. None of these 'near the bottom' figures take infaunal animals into account.

A similar comparison using the 1981 data is not feasible because horizontal tows rather than vertical hauls were used to sample the water column. The epibenthic biomass at Station N-4 was 0.35 g/m^2 (s.d. 0.11) and was comprised primarily of Mysis litoralis. However, it is interesting to note that at Station N-13 on 25 August, at a time and place when whales were observed surfacing with mud streaming from their mouths, 3 horizontal tows were conducted at a 10 m depth (within about 0.5 m of the bottom) to collect epibenthic invertebrates. At this location, using the horizontal tow method (n = 3), total zooplankton biomass averaged 0.41 g/m^3 (s.d. = 0.34); copepods and hydrozoans provided the bulk of the biomass but mysids (primarily Mysis litoralis) also contributed significant, although highly variable, amounts.

As was the case with the mysids in the water column, only a single mysid species (Mysis litoralis) was identified from the drop net collections in both 1980 and 1981. M. litoralis has a circumpolar distribution (Holmquist 1958) and is the most abundant species of mysid, in terms of numbers and biomass, reported along the Beaufort Sea coast (Broad et al. 1980; Griffiths and Dillinger 1981). The latter authors give a detailed description of the biology of M. litoralis and its importance in trophic pathways in nearshore waters of the Alaskan Beaufort Sea. In these waters the biomass of M. litoralis was at least an order of magnitude greater near the bottom than in the water column (on a mg/m^2 basis), even at the deepest station sampled (7.5 m). Although no quantitative data on mysid biomass in waters deeper than

7.5 m in the Alaskan Beaufort Sea are available, mysid swarms probably occur in deeper waters; bowheads feeding off Kaktovik, Alaska, where depths exceed 10 m contained substantial quantities of mysids.

Only one species of isopod (Saduria entomon) was collected during the study. Lowry and Burns (1980) found a few S. entomon in the stomachs of one bowhead taken at Kaktovik, Alaska. Numerous studies have shown that this isopod occurs in the shallow nearshore waters all along the Beaufort Sea coast. A detailed study of the distribution and biology of S. entomon in the Canadian Beaufort Sea has been conducted by Bray (1962).

The almost complete absence of amphipods from the drop net samples (Appendix Table 6) cannot be totally explained; however, it may be partially a reflection of the relatively small number of samples collected. The drop net sampler is known to be capable of collecting epibenthic amphipods when they are present (Griffiths and Dillinger 1981).

Mysids and isopods, the main contributors to the biomass near the bottom at King Point, are generally considered to be predominantly epibenthic. Both mysids and isopods have been found in stomach contents of bowheads off northern Alaska. These results are consistent with the possibility that bowheads acquire a significant amount of food from near-bottom waters. However, this line of evidence for epibenthic feeding is inconclusive because very few isopods were found in bowhead stomachs and because the mysids that were found could have come from occasional occurrences well above the bottom.

Infauna

Although no collections of infaunal organisms were made during this study, previous studies of the distribution, species composition, and biomass of the infauna in the southern Beaufort Sea allow us to estimate the biomass of these organisms in the region where bowhead whales were observed. In 1980, bowheads were typically observed in waters 15-30 m deep off the Tuktoyaktuk Peninsula while in 1981 most were observed in waters 30-60 m deep (see 'Normal Behavior' section). These depths correspond to the 'transitional zone' and the beginning of the 'marine' zone for infaunal organisms described by Wacasey (1975). He estimated that the total biomass of the infauna in the 'transitional zone' averages 5 g/m^2 dry weight or 50 g/m^2 wet weight, and that biomass in the 'marine zone' averages 14 g/m^2 and 140 g/m^2, respectively, assuming a 1:10 conversion between dry and wet. The major species in the 'transitional zone' are the polychaete worms *Artacama proboscidea* and *Trochochaeta carica* and the pelecypod mollusc *Portlandia arctica*, and in the 'marine zone' are the polychaete worms *Maldane sarsi* and *Aricidea suecica* and the pelecypod mollusc *Astarte borealis* (Wacasey 1975).

These results suggest that the biomass of the infauna is greater than the combined biomass of both epibenthic invertebrates and zooplankton.

Comparison of Areas Where Bowheads Were and Were Not Observed

For reasons previously mentioned (see Objectives and Methods sections), different sampling techniques were used during the two years of study (i.e. vertical hauls in 1980; horizontal tows in 1981). Thus the results from the two seasons are not directly comparable. However, by analyzing each year's results separately and then comparing general trends, some insight can be gained regarding the central question in this study: do bowhead whales tend to concentrate in areas where zooplankton biomass is highest?

1980 Results

In 1980, vertical haul samples collected at the eight stations in the general area where bowheads were numerous (off Richards Island) were divided into two groups -- samples from stations where bowheads were and were not seen. Stations with whales were defined as those at which aircraft- or boat-based observers had seen bowheads within the previous 24 h. These stations (of which there were five) were purposely located at our best estimates of the whales' previous locations, but there may have been some deviation (perhaps up to 5 km in some cases) from the exact sites. Also, because of currents the water masses may have changed from the times the whales were seen to the times of sampling. It should also be kept in mind that, as a consequence of logistical constraints, the 1980 analysis is based on a limited number of stations (5 associated with whales and 3 where no whales were observed) sampled over a relatively short span of time. Furthermore, all 8 stations were within a relatively small area (10 by 42 km) within a broader area where bowheads were numerous. Thus, it is possible that all 8 of the 1980 stations are representative of bowhead feeding areas.

For this analysis, the biomass estimates from the vertical samples were grouped into four categories--hydrozoans, copepods, others and total--and then transformed to natural logarithms--ln (x + 1). The 1980 data were analyzed using hierarchical analyses of variance to determine whether zooplankton biomasses were consistently different in the presence and absence of bowhead whales. Stations were nested within the 'bowheads present/absent' factor. Six replicate samples were available from each station. The hierarchical analyses were performed using the SAS version 79.3 'NESTED' computer program (SAS 1979).

In 1980, stations where whales were and were not observed differed significantly in terms of hydrozoan, copepod and total biomass, but did not differ significantly for the 'other' group (Table 6). After whale presence/absence effects had been taken into account, among-station differences in biomass were significant for all four groups of zooplankton (Table 6). This suggests that zooplankton were unevenly distributed.

On the basis of transformed 1980 data, hydrozoan biomass and total biomass were significantly higher at stations where no whales were seen, while copepod biomass was significantly higher where whales were seen (Table 6, Fig. 21). The mean biomass (ln [x + 1]) for each zooplankton group at stations where whales were and were not seen is shown below:

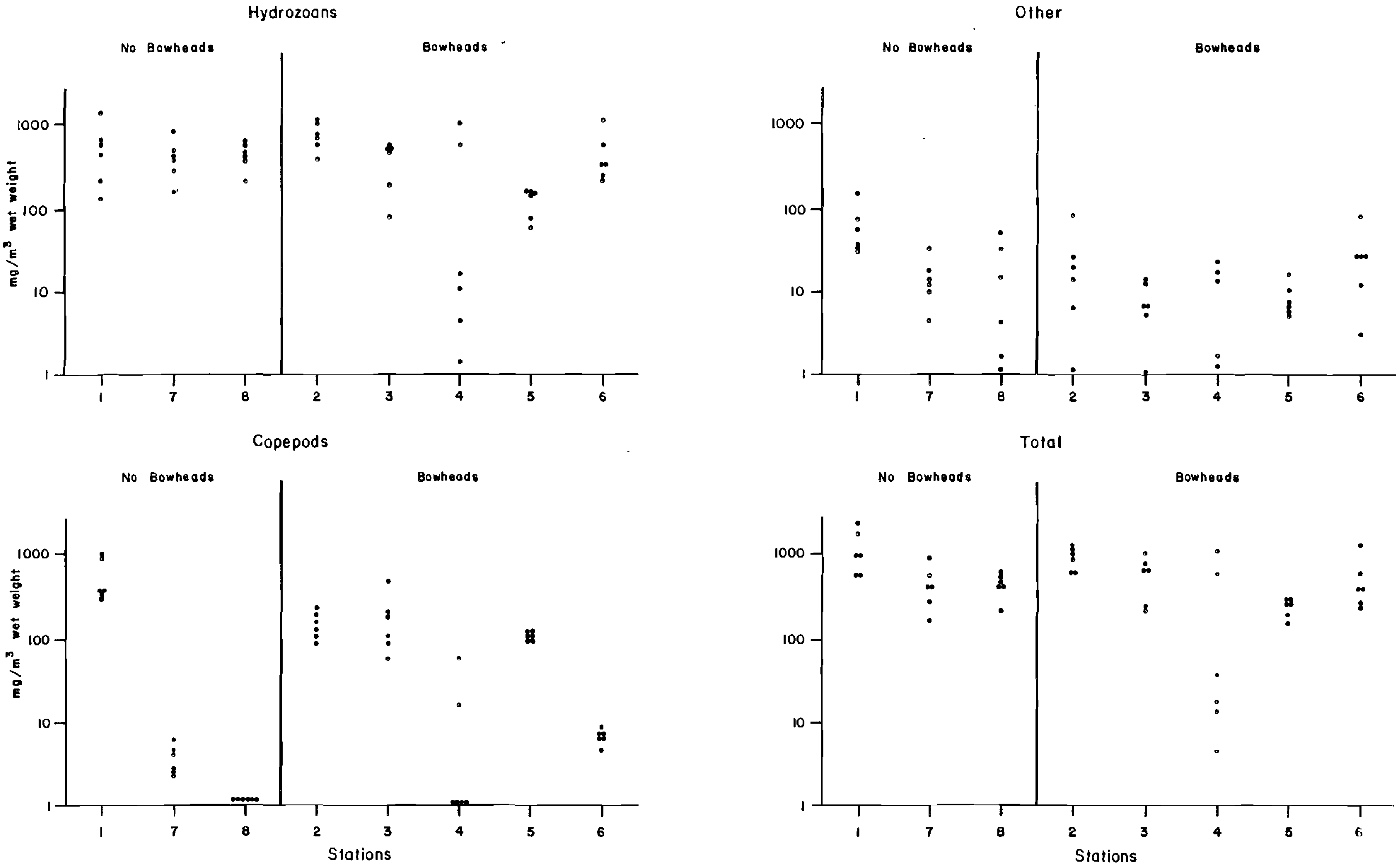
	ln ($mg.m^{-3}$+1)			
	Hydrozoans	Copepods	Other	Total
Whales Not Seen Stations 1,7,8	6.08	2.56	2.89	6.39
Whales Present Stations 2,3,4,5,6	5.38	3.59	2.24	5.78

Differences in total biomass are primarily a reflection of differences in hydrozoan biomass since this group dominated the zooplankton at stations 1-8

Table 6. Comparison of zooplankton biomass [ln (x+1) mg/m^3 wet weight] at 1980 stations in relation to presence and apparent absence of bowhead whales. Data analyzed using hierarchical analysis of variance (SAS 1979).

Group	Factor in ANOVA	Numerator df	Denominator df	F	p
Hydrozoans	Whales*	1	40	4.48	0.0406
	Station	6	40	5.41	0.0004
Copepods	Whales	1	40	20.66	0.0001
	Station	6	40	61.69	0.0001
Other	Whales	1	40	3.78	0.0590
	Station	6	40	2.65	0.0291
Total	Whales	1	40	4.94	0.0320
	Station	6	40	6.16	0.0001

* The 'whales' factor represents the presence or apparent absence of bowheads.



Hydrozoans

Other

Copepods

Total

FIGURE 21. Biomass (mg/m^3 wet weight) of the major groups of zooplankton collected on 14-26 August 1980 off Richards Island, N.W.T., at stations where bowheads were and were not seen. Each point represents one vertical tow from the bottom to the surface. Note that the vertical scale is logarithmic.

(Fig. 21). However, when these results are reviewed in relation to energy equivalents, the importance of copepods is greatly increased (see below) because, on an energy basis, the importance of copepods is much greater than that of the hydrozoans.

In summary, the 1980 results show that copepod biomass was significantly higher in areas where bowhead whales were present than in nearby areas where bowheads were not found. Because copepods are the most important major group of zooplankton in the area in terms of energy content, this result suggests that bowheads select feeding areas where their major food source is most plentiful.

1981 Results

In 1981, horizontal tow samples (three replicates at each of three depths) were collected at two stations where bowhead whales were observed to be feeding. Each of these sets of samples was matched with a similar set of horizontal tow samples taken at a station where bowheads were not observed. The matched 'no bowhead' samples were collected at approximately the same time and in the same general area (N-11 on 24 August vs. N-12 on 24 August; N-9 on 18/19 August vs. L-1 on 11 August) (Figure 2). The 1981 results for the two major groups (copepods and hydrozoans) were analyzed using 2-way ANOVA; the factors were presence or absence of whales and date. The analyses were performed separately on data from surface, mid-depth and bottom samples using the ELF ANOVA2 computer program (Winchendon Group 1980) and log-transformed biomass data (ln [x + 1]).

The 1981 stations where whales were and were not observed differed significantly only in terms of copepod biomass near the bottom and hydrozoan biomass in surface waters (Table 7; Fig. 22). In both cases these biomasses were significantly higher at stations where bowheads were present.

On one occasion (Station N-9, 18-19 August 1981) zooplankton samples were collected in surface waters at the same time as bowhead whales were observed to be feeding at or near the surface (Fig. 18). The total zooplankton biomass and the copepod biomass in surface waters were an order of magnitude greater at Station N-9 (surface feeding whales) than at any of

Table 7. Copepod and hydrozoan biomass [ln (x + 1) mg/m^3 wet weight] in 1981 in relation to presence and absence of bowhead whales. Data analyzed using a 2-way ANOVA for each depth separately; three replicates for each station and depth.

	Factor in ANOVA	df (1, 8)	F	p
Copepods				
Surface	Whales*	1	3.00	>0.10
	Day	1	2.84	>0.10
	Whales.Day	1	4.54	<0.10
	Residual	8		
Mid-depth	Whales	1	0.21	>0.10
	Day	1	0.36	>0.10
	Whales.Day	1	10.16	<0.025
	Residual	8		
Bottom	Whales	1	31.20	<0.001
	Day	1	2.88	>0.10
	Whales.Day	1	1.22	>0.10
	Residual	8		
Hydrozoans				
Surface	Whales*	1	8.88	<0.025
	Day	1	0.08	>0.10
	Whales.Day	1	1.08	>0.10
	Residual	8		
Mid-depth	Whales	1	0.39	>0.10
	Day	1	1.11	>0.10
	Whales.Day	1	2.81	>0.10
	Residual	8		
Bottom	Whales	1	0.003	>0.10
	Day	1	0.72	>0.10
	Whales.Day	1	5.36	<0.05
	Residual	8		

* The 'whales' factor represents the presence or apparent absence of bowheads.

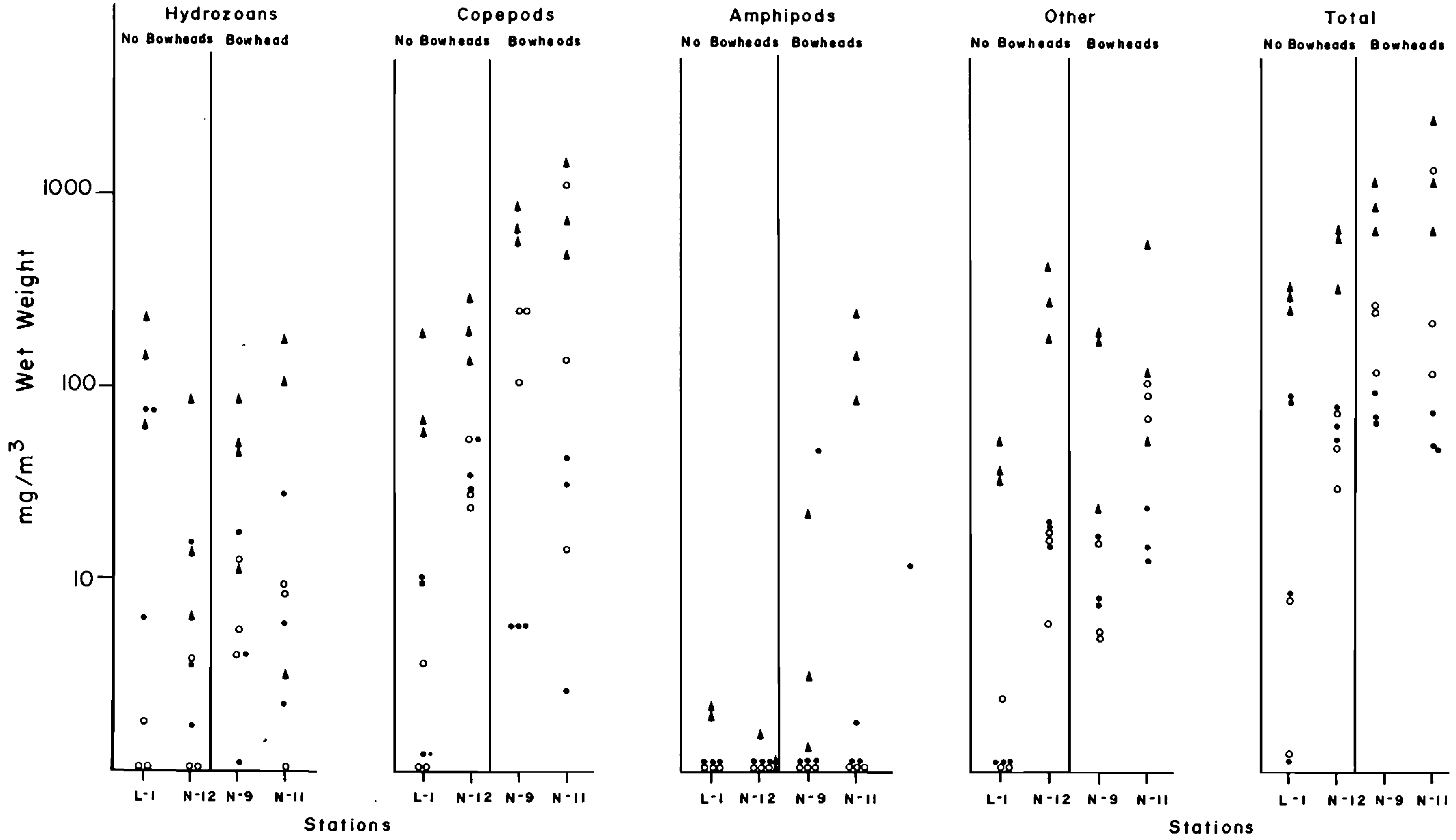


FIGURE 22. Biomass (mg/m^3 wet weight) of the major groups of zooplankton collected 11-24 August off Richards Island, N.W.T., at stations where bowheads were and were not seen. Open circles (∘) surface samples, closed circles (•) are midwater depths, and triangles (▴) are samples from near bottom. Each point represents one horizontal tow. Vertical scale is logarithmic.

Table 8. Comparison of zooplankton biomass (mg/m^3 wet weight) collected at the surface (0-1 m) at Station N-9 where bowheads were observed to be surface feeding and stations where whales were not observed, 1981.

	Whales Observed	No Whales Observed				
	N-9	L-1	N-12	N-8	L-1	L-1
Group	18/19 Aug	11 Aug	24 Aug	14 Aug	1 Aug	6 Sept
Hydrozoans	7.3	0.6	1.9	1.1	1.0	2.9
Copepods	199.5	1.9	34.8	8.3	0.02	1.1
Amphipods	0.7	0	0.02	0	0	0.6
Other	8.6	0.9	13.3	9.2	2.0	1.4
Total	216.1	3.5	49.9	18.7	3.0	5.5
Water Depth	26.0 m	20.0 m	15.0 m	20.0 m	20.0 m	20.0 m

Table 9. Comparison of zooplankton biomass (mg/m^3 wet weight) collected near the bottom at Station N-13 where bowheads were observed feeding near the bottom (mud observed in their mouths) and at stations where bowheads were not observed.

	Whales Observed	No Whales Observed			
	N-13	L-1	N-12	L-1	L-1
Group	25 Aug	11 Aug	24 Aug	1 Aug	6 Sept
Hydrozoans	95.2	145.5	36.3	123.8	15.2
Copepods	252.5	106.7	209.1	30.4	1.1
Amphipods	1.9	1.6	1.0	6.1	6.8
Other	64.0	40.4	284.4	135.4	36.5
Total	413.6	294.2	530.8	295.6	49.4
Water Depth	10.5 m	20.0 m	15.0 m	20.0 m	20.0 m

the non-whale stations (Table 8). This suggests that, at least when surface feeding, bowheads utilize areas that have greater accumulations of zooplankton than are typically found in the region.

A similar whale/non-whale comparison using Station N-13, where bowhead whales were observed bottom feeding (i.e. mud seen in their mouths), is shown in Table 9. In this case, the differences are not as apparent. The total zooplankton biomass was not highest at the whale station; however, the copepod biomass was somewhat higher there than at any other station. This suggests that if the copepod biomass is high enough, whales will feed in areas where the total zooplankton biomass is near-average.

General Trends, 1980-1981

The results from both 1980 and 1981 (although collected using different techniques) showed that bowhead whales appear to congregate in areas where copepod biomass is high in relation to that in other sampled areas. In both years, two species of copepod (*Calanus hyperboreus* and *C. glacialis*) comprised the dominant portion of the copepod biomass. Several species of copepods have been reported from stomachs of bowhead whales taken at Point Barrow and Kaktovik, Alaska; however, *C. hyperboreus* was the most common of these species (Lowry and Burns 1980; Frost and Lowry 1981; Marquette et al. 1981).

In 1980 hydrozoans comprised the major portion of the zooplankton biomass, and in 1981 they were the second most important group, after copepods, in terms of biomass. Analyses of bowhead whale stomachs from the Alaskan Beaufort Sea show that copepods were a major food item, while hydrozoans did not appear in the stomachs at all (Lowry and Burns 1980). However, the absence of hydrozoans from bowhead stomachs may be due to a combination of their fragile nature and rapid digestion in whales. If, as seems likely, bowheads receive a portion of their energy intake from hydrozoans, the abundance of copepods appears to be the main factor affecting choice of feeding locations. Bowheads may obtain hydrozoans at either type of station but probably are better able to obtain copepods where copepods occur in aggregations.

The importance of copepods in both years is more evident if the energy results are expressed in kilocalories. Estimates of water content and kcal/gram ash-free dry weight for our major zooplankton groups are shown in Table 10. These values are primarily from Percy and Fife (1980) and were obtained from arctic marine invertebrates collected in Frobisher Bay, N.W.T., at the same time of year as our sampling (July-September). Based on this material, copepods had approximately 8 times more dry weight per gram of wet weight than did hydrozoans ([100-65.5]/[100-95.7] = 34.5%/4.3% = 8.02). Copepods in the Frobisher Bay material also contained 63.9% more energy per gram of ash-free dry weight than did hydrozoans (7.58 + s.d. 0.35 vs. 4.84 ± s.d. 0.99). Based on these two ratios, copepods from the Frobisher Bay area collected between July-September 1980 contained about 13 times as much energy per gram of wet weight as did hydrozoans (8.02 x 1.64). If this ratio is applied to the eastern Beaufort Sea between July and September in 1980 and 1981, the importance of copepods relative to that of hydrozoans would be greatly increased in relation to the biomass figures shown in the diagrams and tables in this report.

Food Requirements and Availability

Food Requirements of Bowhead Whales

The daily requirements of bowhead whales are not known; however, it is possible to calculate a range of estimates from available information about whales in general and bowheads in particular. Because the literature contains a variety of values for some of the important factors used in a calculation such as this (e.g., area of the mouth opening, the daily food ration, etc.), a range of estimates has been calculated.

In these calculations a bowhead whale 13.5 m in length and 45 metric tonnes in weight is assumed. The 13.5 m figure corresponds to the average size of bowheads commonly observed during the study (LGL Ltd., in prep.), and the weight is consistent with the length:weight ratio reported for Pacific right whales by Nemoto (1970) and for bowhead whales by Brodie (1981).

The density of prey items required shows a wide range depending on the assumptions used. In the extreme cases (i.e. mouth opening 1.0 m^2 and daily

Table 10. Summary of water content as percent of live weight and Kcalories per gram ash-free dry weight of marine invertebrates commonly found in study area. Values in this table are from samples collected in Frobisher Bay (Percy and Fife 1980).

Group	Water content as percent of live weight		Kcalories/g ash-free dry weight	
	Mean	s.d.	Mean	s.d.
Hydrozoans				
Halitholus cirratus	95.9	0.2	5.80	0.28
Aglantha digitale	95.6	-	4.80	0.15
Sarsia princeps	95.6	-	3.82	0.71
All Hydrozoans	95.7	-	4.84	0.99
Copepods				
Calanus spp.[1]	65.5	4.5	7.58	0.35
Amphipods				
Parathemisto libellula	77.8	1.8	6.09	0.77
Gammarus setosus	77.6	2.9	5.59	0.08
Onisimus litoralis	73.9	1.6	6.01	-
Other[2]				
A mean value	-	-	6.11	-
B mean value	-	-	5.29	-

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[1] Primarily *Calanus glacialis* and *C. hyperboreus*.

[2] Others A includes euphausiids (Percy and Fife 1980) and mysids (Griffiths and Dillinger 1981).

Others B includes ctenophores, chaetognaths, gastropods (i.e. pteropods).

ration of 1800 kg; mouth opening 8.9 m^2 and daily ration 585 kg) the range is 90 g/m^3 to 3.3 g/m^3 for a bowhead swimming at 4 km/h and feeding for 5 h. For the remainder of these calculations an intermediate value (i.e. the last line in Table 11) will be used.

Table 11. Daily food requirements and density (g/m^3 wet weight) of zooplankton required to provide daily ration in 5 and 10 h for a 13.5 m, 45 tonne, bowhead whale swimming at 4 km/h.

Effective Cross Sectional Area of Mouth Opening (m^2)	Daily Food Ration		Density (g/m^3) of Zooplankton Required if Daily Duration of Feeding is	
	As Percent of Body wt.[1]	Kg wet wt.	5 h	10 h
1.0 (Brodie 1980)	1.3%	585 (Brodie 1981)	29.3	14.6
8.9 (Nemoto 1970)	4.0	1800 [Sergeant 1969; Slijper 1962]	10.1	5.1
5.0 (mean of above)	2.7	1192 (mean of above)	11.9	6.0

[1] Based on whale feeding only six months of the year; on an annual basis the average values would be 0.65%, 2.0% and 1.85%, respectively.

Availability of Zooplankton to Bowhead Whales

A major problem in sampling zooplankton with nets is that large distances must be covered in order to obtain adequate samples. Consequently, each sample represents the average density or biomass of the zooplankters in a large volume of water (Brodie et al. 1978). It is well known that the average distribution of zooplankton in an area does not accurately reflect the actual distribution since zooplankters commonly concentrate in both the vertical and horizontal planes on scales varying from metres to kilometres (Brodie et al. 1978; Sekerak et al. 1979). In 1980 this problem, combined with the small number of samples collected, prevented us from evaluating the extent of zooplankton aggregations in areas where bowheads were common. In 1981 an echosounder was used to search for dense concentrations (layers) of zooplankton in the water column, and then samples of these layers were collected and related to bowhead distribution and feeding behavior.

Could a bowhead whale obtain its daily food requirement if the average densities of zooplankters determined from net samples were an accurate estimate of the actual densities in places where whales feed? The following analysis of this question is similar to the analysis of fin whale feeding by Brodie et al. (1978). In 1980, the average zooplankton biomass collected in vertical tows at Stations 2-6 (stations where bowheads were observed) was assumed to represent the zooplankton biomass available to bowheads. In 1981, the available biomass was assumed to be the average biomass at all depths at stations where bowheads were observed feeding (i.e. Stations N-9, N-11, N-10 and N-13). The mean biomass estimates for each major group and overall for 1980 and 1981 are shown below:

	mg/m^3 wet weight	
Group	1980	1981
Hydrozoans	442.2	34.6
Copepods	99.9	323.0
Other	16.1	91.9
Total	558.2	449.4

Based on the total zooplankton biomass (about 0.5 g/m^3) figure and the average bowhead calculations from Table 11, it appears that, in 1980 and 1981, a bowhead whale would have required 107 h and 133 h, respectively, to obtain the food that it is calculated to require in each 24 h period. Clearly this scenario is incorrect. It would appear that bowheads must concentrate their feeding in areas or at water depths where zooplankton biomass is somewhat greater than the averages found near whales in 1980 and 1981. For example, if we use the maximum zooplankton biomass estimate (2.5 g/m^3) obtained during this study, then bowheads feeding exclusively in locations with food abundance equivalent to this value would require about 24 h to obtain their daily energy requirement. Alternatively, if we assumed that they fed throughout the year (as opposed to only 6 months), then they presumably could survive on zooplankton concentrations of 2.5 g/m^3 by feeding 12 h/day. Whether these areas of greater than average biomass recur year after year in the same region, or are more transitory in nature, is not known. It is clear, however, that the distribution of bowheads in the summers of 1980 and 1981 was different (Würsig et al. 1982; LGL Ltd., in prep.).

In a similar analysis for fin whales and euphausiids off Nova Scotia, Brodie et al. (1978) found that a fin whale would have to travel 7000 km per day to obtain the daily food requirement from the average density of euphausiids as determined by nets--i.e. at a speed of approximately 900 km/h to obtain the daily requirement in 8 h. They concluded that fin whales must feed selectively in areas where euphausiid densities are far greater than the average indicated by net sampling. They also reported that studies using echosounders and multiple opening and closing nets had found that euphausiids occurred in aggregations dense enough to provide for the dietary needs of fin whales (Sameoto and Paulowich 1977; Brodie et al. 1978). Although not directly observed, a similar phenomenon is likely to occur in the southern Beaufort Sea, where localized aggregations of zooplankton may be utilized by bowheads to obtain their daily food requirements.

The above analysis suggests that selectivity by bowheads for areas of high food abundance need not be as great as that by fin whales. The comparatively modest concentrations of food that bowheads may utilize would probably go undetected by a limited sampling program utilizing vertical or horizontal tows. During this study, observers in aircraft did not see any broad patches of plankton at the surface. In contrast, Watkins and Schevill (1976, 1979) saw right whales skim feeding at the surface on patches of plankton that were visible to observers in aircraft. Groups of feeding bowheads did, however, tend to be dispersed over a relatively large area, and individuals or subgroups tended to stay in a small area (at least during the observation period). This suggests that the plankton may have been concentrated in particular areas. Nonetheless, bowheads (and other right whales) with their very large mouths and large amounts of baleen are apparently well adapted to strain comparatively dilute plankton from the water. They may be less dependent on extremely dense patches of food than are certain other whales (Nemoto 1970; Pivorunas 1979).

Although no broad patches of plankton were noticed in either 1980 or 1981, linear concentrations of zooplankton were observed in 1980, from both aircraft and boats, in areas utilized by bowhead whales. These linear concentrations were typically observed in calm to moderate seas in the latter half of August, and are believed to occur along 'fronts' or boundaries between the warmer nearshore waters and the cooler offshore waters (e.g.

Brown 1980). Observations from the 'Imperial Sarpik' suggested that the zooplankton along these 'fronts' consisted mainly of copepods. Elsewhere densities of zooplankton along 'fronts' can be as much as 75 times greater than in the surface waters on either side (Brown 1980). Although bowheads were seen near these concentrations in 1980, none were observed to feed along the 'fronts'. On a single occasion a lone bowhead was seen to pass at right angles through a 'front' but it made no attempt to swim along it.

During 1981, 'fronts' of two types were observed in the study area. (1) The most common type separated clear offshore water from the more turbid plume of the Mackenzie River. These 'fronts' were common and fairly extensive; however, no obvious aggregations of zooplankton were observed hydroacoustically when the ship crossed over them. (2) On at least one occasion (off Cape Bathurst) a series of bright orange lines was observed from the aircraft. They appeared similar to the material (probably consisting mainly of copepods) along 'fronts' observed from the 'Imperial Sarpik' in 1980. No 'fronts' of this second type were observed from the boat in 1981, and no bowheads were observed along either type of 'front' in 1981.

Although the extent of the feeding area of bowhead whales in the Beaufort Sea is not known, by using some of the above assumptions an estimate of the area required can be calculated. It is important to remember that such an estimate is based on a series of assumptions and extrapolations, any of which could be substantially in error. The result is at most a useful basis for speculation. The data from the vertical hauls are used here because vertical hauls are much more representative of the total biomass in the water column than are horizontal tows. If bowheads feed exclusively on zooplankton and if we assume a daily requirement of 1192 kg wet weight per bowhead, an average zooplankton biomass of 0.558 g/m^3 wet weight (mean from 1980 vertical hauls at all stations in the general area where whales were observed), a population of 2264 bowheads (Braham et al. 1980), and a 100 day residence period in the eastern Beaufort Sea, these bowheads would require all of the zooplankton in an area of about 9,675 km^2 (e.g. an area of 50 x 193 km) if the average water depth were 50 m. If it is further assumed that bowheads obtain half of their yearly food requirement while in the eastern Beaufort Sea, then they would need all the zooplankton in an area of 17,653 km^2 (e.g. an area 50 x 353 km) if the average depth were 50 m.

The above calculations suggest that there is easily enough zooplankton in the Beaufort Sea to support the present population of bowheads, even if the mean zooplankton biomass is no higher that that recorded by net sampling. Considering longitudes from the Alaska-Yukon border east to Cape Dalhousie, the area of water less than 100 m deep exceeds 54,200 km^2. The limiting factor would appear to be the time needed to filter the required volume of water, the difficulty in finding concentrations of zooplankton, or both.

Food availability (as well as filtering capacity) might have been a more important factor previous to commercial exploitation of the western arctic bowheads. Based on calculations comparable to those above, a population of 20,000 bowheads would require all the zooplankton in an area of 85,448 km^2 (e.g. 50 x 1709 km) to obtain a 100-day supply of food, assuming an average water depth of 50 m. Previous to commercial exploitation, western arctic bowheads apparently summered in the northern Bering, Chukchi and westernmost Beaufort seas as well as the eastern Beaufort Sea (Townsend 1935; cf. Dahlheim et al. 1980; Fraker and Bockstoce 1980). The historical summering range (mid June - mid September) was probably considerably more than 85,448 km^2, but it is doubtful that the present summering range is that large.

Based on the filtering capacity argument given above and observations of the feeding of right whales (Watkins and Schevill 1976, 1979), bowheads probably concentrate their feeding in areas where zooplankton is denser than average. The 0.558 g/m^3 figure for zooplankton biomass used in the above calculations is based on the mean zooplankton biomass from 1980 vertical haul samples in the general area where bowheads were feeding, but probably under-represents mean zooplankton biomass in the exact locations where bowheads fed. If so, then the volume of water that must be filtered and the required size of the summer range would be lower than calculated above. Note also that the above calculations do not allow for zooplankton production within the 100-day period under consideration. The production to biomass ratio for a 100-day period in summer is roughly 1.45 (Parsons et al. 1977).

In summary, these speculations suggest that the present-day population of bowheads could subsist in summer on zooplankton alone if they can filter a sufficient volume of water. A larger historical population of perhaps 20,000 animals might have done so also, but probably only by occupying a larger summer range than is now used. In any event, the calculations suggest that bowheads may exert significant cropping pressure on zooplankton, at least in local areas, if zooplankton is the primary food source. In order to confirm, refute or refine these speculations, additional data are needed on zooplankton biomass and patchiness over the breadth of the Beaufort Sea and in specific places where bowheads feed.

Potential Importance of Benthos to Bowheads

Two other possible sources of food have not been considered in the previous analysis--epibenthic invertebrates on or near the bottom, and infaunal organisms in the bottom substrate. The extent to which bowheads utilize these resources is not known but suggestions of bottom feeding have been relatively common in the few bowhead stomachs containing food items that have been available (see 'Introduction'). In this study, definite indications of bottom feeding were obtained; however, this was observed in only one area and on only two days during August 1980, and in one area on one day in 1981 (see 'Normal Behavior' section). If bowheads feed in areas that have the maximum epibenthic biomass found in this study and the maximum infaunal biomasses reported for the 'transition zone' (1.3 and 50 g/m^2, respectively), and if they consume 100% of the benthic animals present, then each bowhead would have to denude 23,236 m^2 daily (e.g. an area 152 m square) to obtain its required food needs. Only the value for the 'transition zone' is used here, so the area required represents a maximum. If the whales feed in the 'marine zone' where benthic biomass is greater, then less area would be required by each whale for its daily food needs.

Based on these assumptions, the total present-day population of bowheads in the western arctic, about 2264 animals (Braham et al. 1980), would have to denude an area of about 5261 km^2 over a 100 day period if only benthos (inbenthos plus epibenthos) were consumed. If only epibenthic animals were consumed, the area required would be implausibly large (about 0.9 km^2 per bowhead per day, or about 207,591 km^2 for 2264 bowheads over 100 days). The above areas would be larger if average rather than maximum benthic biomass were assumed, if <100% cropping efficiency were assumed, or if present-day population size is larger than 2264 animals.

These calculations suggest that infaunal benthic animals, if exploitable by bowheads, could provide a major source of food, but epibenthic animals likely would be important only if bowheads could exploit dense patches of these animals. It must be emphasised that few if any bowhead whales obtain their total daily food requirements by consuming infaunal benthic animals; their baleen (long, slender, elastic) and mouth shape are more adapted to filter large volumes of water, and bottom feeding was relatively uncommon in both 1980 and 1981.

The Feeding Strategy of Western Arctic Bowheads

The results of stomach analysis of bowheads indicate that zooplankton in the water column and epibenthic invertebrates on or near the bottom are the most important sources of food, but that some feeding on infaunal organisms occurs at least incidentally (see 'Introduction'). The relative importances of water column, epibenthic and infaunal organisms in the diets of bowheads are unknown, but from the data collected in 1980 and 1981 and calculations above it seems apparent that bowheads must feed on aggregations of zooplankton, in excess of average amounts collected in net samples, in order to obtain their daily food requirement in a realistic amount of time. The closely related right whale sometimes concentrates in the densest patches of plankton and actively turns away from sparse areas and toward areas where plankton is more concentrated (Watkins and Schevill 1976, 1979).

The results from both years of study suggest the possibility of a form of food limitation since bowheads appear to require zooplankton aggregations in order to obtain the needed food in a reasonable length of time. Consequently, the exclusion of whales from areas containing these concentrations could be deleterious.

Data from this and previous studies suggest that bowhead whales feed along much of the Beaufort Sea coast of Canada and Alaska at some time during summer and fall. It has been suggested that the Beaufort Sea is the primary feeding area for this species. If bowhead whales do indeed move into the Beaufort Sea to feed during the open water period, it is interesting to note that in leaving the Bering Sea (the wintering grounds) they are leaving a more productive area. A comparison of total annual primary production in the

Beaufort and Bering Seas shows the Bering Sea to be much more productive (i.e. 75-250 g $C.m^{-2}.yr^{-1}$ vs. 10-15 g $C.m^{-2}.yr^{-1}$, McRoy and Goering [1976] and Alexander [1974], respectively). The difference in zooplankton biomass is not as great; in the case of comparable vertical zooplankton haul samples, the overall average for the Bering Sea is only about twice that for the eastern Beaufort Sea (60.4 g/m^2 vs. 28.0 g/m^2, Ikeda and Motoda [1979] and this study, respectively). Furthermore, this difference is in part attributable to the greater mean depth at sampling locations in the Bering Sea (150 m vs. 50 m, respectively). Unfortunately, there are no comparable values for horizontal tows. A further consideration is that most zooplankton have a two year life-cycle in the Beaufort Sea compared to a one year life-cycle in the Bering Sea; consequently the turnover rate for carbon is approximately twice as fast in the Bering Sea.

A detailed cost/benefit analysis for the migration of Western Arctic bowheads would have to consider the seasonal variation in productivity and in zooplankton biomass in each area, the effects of depth and plankton patchiness on food availability, the energy cost of swimming from the Bering to the Beaufort Sea and back, and the effects of the different thermal regimes at different seasons and places. Available data concerning most of these factors are too imprecise for a meaningful analysis at this time. However, the few data summarized in the previous paragraph suggest that bowheads may move into the Beaufort Sea for reasons unrelated to the relative amounts of zooplankton produced in the two areas.

CONCLUSIONS

1. Water Masses in the Study Area

Typically, two distinct parcels of water are found in the nearshore shallow water region of the southern Beaufort Sea. At the surface there is a warm (2.6-11.3°C) brackish (9-25 ppt) layer, formed from a combination of (1) the outflow of warm fresh water from the Mackenzie River and (2) nearshore ice-free marine water. Below this layer is a colder (-1.5 to 6.3°C) and more saline (23-32 ppt) layer of marine bottom water of Arctic surface water origin.

2. Biomass in the Water Column

In 1980 hydrozoans and copepods were, in terms of biomass, the two main groups in the water column (range: 1302-12 mg/m^3 wet weight) in the general area where bowheads were feeding during August and early September. In 1981, horizontal tows showed copepods and hydrozoans to be the two main groups (range: 2456-0.06 mg/m^3). In both years, five species of hydrozoans (*Halitholus cirratus*, *Euphysa flammea*, *Sarsia princeps*, *Aglantha digitale*, *Aeginopsis laurentii*) and five species of copepods (*Calanus hyperboreus*, *C. glacialis*, *Limnocalanus macrurus*, *Pseudocalanus minutus*, *Derjuginia tolli*) accounted for most of the biomass.

3. Biomass On or Near the Bottom

Mysids (*Mysis litoralis*), isopods (*Saduria entomon*) and to a lesser extent copepods and hydrozoans accounted for the major portion of the biomass on or near the bottom in both 1980 and 1981 (1980: 1313-424 mg/m^2 wet weight; 1981: 350 mg/m^2).

4. Infaunal Biomass

Infauna were not studied, but previous work indicates that the estimated total biomass of the infauna averages 50 g/m^2 in waters 15-30 m deep and 140 g/m^2 in waters 30-60 m deep. It consists mainly of polychaete worms and bivalve molluscs at all depths considered.

5. Comparison of Stations where Bowheads were and were not Observed

Results from both years of the study suggest that bowhead whales tend to be found in areas that have significantly higher biomass of copepods than in surrounding areas. In 1980, areas with bowheads may also have had lower biomass of hydrozoans and lower total biomass than did areas where no bowheads were seen. However, this was not the case in 1981. In 1980, no differences were evident in the temperature and salinity profiles in the two types of areas. In 1981, stations at which bowheads were observed feeding did not have distinct thermo- and haloclines compared to stations where no whales were observed. All of the locations considered in both 1980 and 1981 were within the general area where bowheads were feeding.

6. Trophic Relationships

Previous analyses of bowhead whale stomachs and observations made during this study ('Normal Behavior' section) suggest that bowheads get the major portions of their daily food requirement from the water column and on or near the bottom, with a possible minor contribution from infaunal organisms. If zooplankton are the primary food source, it appears that bowheads must concentrate their feeding in areas with aggregations of zooplankton in order to get their daily ration in a realistic amount of time.

The abundance of hydromedusae in the zooplankton within an area of the eastern Beaufort where bowheads were feeding (and also in the Alaskan Beaufort--Horner 1979) suggests that these animals are an important part of the bowhead diet. Their apparent absence from the bowhead stomachs examined to date may be an artefact of the fragile nature of these medusae and the reportedly rapid digestive processes in whales. However, it must be remembered that the energetic value of copepods is approximately 13 times that of hydrozoans on the basis of wet weight.

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Appendix Table 1. Biomass (mg/m^3 wet weight) of zooplankton collected in vertical tows at stations off Richards Island, N.W.T., 14 August 1980. Each mean and standard deviation is based on six replicate samples.

Date	14 August 1980					
Station	1		2		3	
Location Lat.	69°56'N		70°00'N		70°01'N	
Long.	134°23'W		134°16'W		134°04'W	
Depth (m)	12		17		19.5	
Group or Species	Mean	S.D.	Mean	S.D.	Mean	S.D.
HYDROZOA						
Sarsia princeps	23.95	49.36	5.57	8.78	-	-
Halitholus cirratus	336.13	370.39	2208.33	104.87	83.92	174.56
Rathkea octopunctata	4.42	1.55	4.16	1.88	8.15	4.36
Euphysa flammea	221.47	115.43	557.02	223.83	91.40	67.23
Obelia sp.	0.14	0.22	0.30	0.26	0.49	0.37
? *Phialidium languidum*	-	-	-	-	P	-
? *Margelopsis hartlaubi*	1.13	1.80	8.28	19.82	0.37	0.62
Aglantha digitale	10.94	5.50	14.08	6.57	34.60	16.25
Aeginopsis laurentii	12.24	18.75	17.78	6.90	8.90	5.00
CTENOPHORA - damaged	3.45	8.45	13.18	27.17	5.08	8.53
POLYCHAETA						
Aphroditidae	2.70	6.62	-	-	-	-
unid. juvenile	P	-	P	-	P	-
PTEROPODA						
Limacina veliger	-	-	P	-	P	-
CUMACEA - unid.	0.02	0.05	-	-	-	-
CIRRIPEDIA - cypris	P	-	-	-	-	-
CALANOIDA						
Calanus glacialis	30.28	15.86	9.06	2.32	4.21	3.51
C. hyperboreus	581.26	341.17	148.35	52.95	199.78	170.97
Pseudocalanus minutus	3.30	3.26	2.26	0.38	0.28	0.22
Derjuginia tolli	5.85	6.58	0.26	0.19	P	-
Euchaeta glacialis	0.22	0.47	0.12	0.29	-	-
Scolecithricella minor	P	-	P	-	P	-
Metridia longa	2.46	1.81	1.09	0.59	0.33	0.47
Acartia longiremis	P	-	P	-	-	-

Appendix Table 1. Concluded.

Date	14 August 1980					
Station	1		2		3	
Location Lat.	69°56'N		70°00'N		70°01'N	
Long.	134°23'W		134°16'W		134°04'W	
Depth (m)	12		17		19.5	
Group or Species	Mean	S.D.	Mean	S.D.	Mean	S.D.
CYCLOPOIDA						
Oithona similis	P	-	P	-	P	-
Oncaea borealis	-	-	P	-	P	-
MYSIDACEA						
Mysis litoralis	43.19	34.03	2.61	6.38	-	-
DECAPODA - juvenile	-	-	0.36	0.89	0.20	0.48
AMPHIPODA						
Hyperia galba	0.99	1.60	0.55	0.84	0.52	1.02
Hyperiid juvenile	0.08	0.12	P	-	0.02	0.04
CHAETOGNATHA						
Sagitta elegans	18.54	20.45	16.24	21.14	2.03	1.78
LARVACEA						
Oikopleura sp.	-	-	-	-	P	-
UNID. - invert. larva	-	-	0.03	0.06	0.10	0.10
PISCES						
Boreogadus saida	-	-	6.98	10.57	3.87	5.04
TOTAL	1302.75	813.91	1016.72	366.89	644.21	346.52

P = <1 mg in a sample.
? = I.D. not verified.

Appendix Table 2. Biomass (mg/m^3 wet weight) of zooplankton collected in vertical tows at stations off Richards Island, N.W.T., 24-26 August 1980. Each mean and standard deviation is based on six replicate samples.

Date		24 August		26 August			
Station		4		5		6	
Location	Lat.	69°56'N		70°04'N		69°59'N	
	Long.	134°55'W		134°19'W		134°18'W	
Depth (m)		17		25.7		19.3	
Group or Species		Mean	S.D.	Mean	S.D.	Mean	S.D.
HYDROZOA							
Sarsia princeps		-	-	18.68	27.88	-	-
Halitholus cirratus		125.95	247.96	51.41	48.46	214.73	140.93
Rathkea octopunctata		4.05	3.03	5.01	3.97	10.10	2.94
Euphysa flammea		156.51	242.54	18.16	23.52	237.31	238.11
Obelia sp.		1.10	0.85	1.07	0.36	1.58	0.73
? *Phialidium languidum*		-	-	-	-	0.41	0.64
? *Margelopsis hartlaubi*		0.83	2.03	1.84	3.74	10.43	14.52
Aglantha digitale		4.75	6.23	17.91	5.90	35.65	19.89
Aeginopsis laurentii		3.36	3.83	3.25	1.83	8.20	3.29
CTENOPHORA - damaged		-	-	16.62	16.74	-	-
PTEROPODA							
Clione veliger		-	-	P	-	P	-
POLYCHAETA - juvenile		P	-	P	-	-	-
CIRRIPEDIA - cypris larva		P	-	P	-	P	-
CALANOIDA							
Calanus glacialis		0.53	0.85	37.23	7.26	2.17	1.25
C. hyperboreus		12.43	24.27	77.14	7.20	4.00	1.99
Pseudocalanus minutus		0.18	0.33	0.03	0.07	0.10	0.06
Derjuginia tolli		-	-	P	-	P	-
*Limnocalanus macrurus***		-	-	P	-	-	-
HARPACTICOIDA							
Harpacticus sp.		-	-	P	-	-	-
MYSIDACEA							
Mysis litoralis		3.03	7.42	-	-	-	-
DECAPODA - juvenile		0.12	0.29	0.12	0.29	-	-

Appendix Table 2. Continued.

Date	24 August		26 August			
Station	4		5		6	
Location Lat.	69°56'N		70°04'N		69°59'N	
Long.	134°55'W		134°19'W		134°18'W	
Depth (m)	17		25.7		19.3	
Group or Species	Mean	S.D.	Mean	S.D.	Mean	S.D.
AMPHIPODA						
Hyperia galba	-	-	0.19	0.46	0.62	1.22
Parathemisto libellula	-	-	-	-	1.88	4.60
Hyperiid juvenile	0.03	0.06	P	-	0.07	0.13
Gammarus wilkitzkii	2.07	5.07	-	-	-	-
Gammarid juvenile	-	-	-	-	0.03	0.08
ECHINODERMATA						
Ophiuroid - juvenile	-	-	P	-	P	-
- plutei	-	-	P	-	-	-
CHAETOGNATHA						
Sagitta elegans	0.03	0.06	2.90	1.55	2.85	3.86
LARVACEA						
Oikopleura sp.	-	-	P	-	-	-
UNID. - invert. larva	P	-	P	-	0.07	0.08
PISCES						
Boreogadus saida	5.57	11.33	4.77	2.89	6.77	5.66
Liparis sp.	-	-	-	-	12.01	29.41
Cottidae	-	-	-	-	3.52	8.62
TOTAL	320.50	503.40	256.31	57.76	553.25	398.10

? = I.D. not verified.
** = probably sub-species *grimaldi*.
P = <1 mg in a sample.

Appendix Table 2. Continued.

Date	26 August			
Station	7		8	
Location Lat.	69°59'N		69°56'N	
Long.	134°18'W		134°18'W	
Depth (m)	19.3		10.2	
Group or Species	Mean	S.D.	Mean	S.D.
HYDROZOA				
Sarsia princeps	64.02	81.33	-	-
Halitholus cirratus	251.95	227.40	337.83	177.83
Rathkea octopunctata	0.45	0.31	5.67	2.92
Euphysa flammea	103.89	52.65	58.29	63.74
Obelia sp.	7.48	1.92	2.92	1.76
? *Phialidium languidum*	0.96	2.35	0.44	1.08
? *Margelopsis hartlaubi*	19.86	33.18	33.38	52.08
Aglantha digitale	24.73	8.46	10.49	5.28
Aeginopsis laurentii	0.48	0.31	2.18	2.46
? *Eumedusa birulai*	-	-	0.33	0.80
POLYCHAETA - juvenile	-	-	P	-
PTEROPODA - *Clione* veliger	P	-	P	-
ISOPODA	-	-	P	-
CIRRIPEDIA - Cypris larva	P	-	P	-
CALANOIDA				
Calanus glacialis	1.61	1.49	-	-
C. hyperboreus	1.21	0.70	-	-
Pseudocalanus minutus	P	-	P	-
Derjuginia tolli	-	-	P	-
*Limnocalanus macrurus***	-	-	P	-
Acartia longiremis	P	-	-	-
EUPHAUSIACEA - juvenile	P	-	-	-
MYSIDACEA				
Mysis litoralis	-	-	2.24	5.48
AMPHIPODA				
Hyperia galba	4.06	6.75	0.05	0.14
Hyperiid juvenile	P	-	0.06	0.10
Oedicerotid juvenile	-	-	P	-

Appendix Table 2. Concluded.

Date	26 August			
Station	7		8	
Location Lat.	69°59'N		69°56'N	
Long.	134°18'W		134°18'W	
Depth (m)	19.3		10.2	
Group or Species	Mean	S.D.	Mean	S.D.
ECHINODERMATA				
Ophiuroid - juvenile	P	-	-	-
- plutei	P	-	-	-
CHAETOGNATHA				
Sagitta elegans	8.51	3.64	2.57	4.03
LARVACEA				
Oikopleura sp.	P	-	P	-
UNID. - invert. larva	P	-	P	-
PISCES				
Boreogadus saida	2.07	3.28	4.65	9.47
Cottidae	-	-	7.51	18.40
TOTAL	491.28	281.61	468.60	154.16

P = <1 mg in a sample.
? = I.D. not verified.
** = probably subspecies _grimaldi_.

Appendix Table 3. Biomass (mg/m^3 wet weight) of zooplankton collected in vertical tows at stations off King Point, N.W.T., 21 August 1980. Each mean and standard deviation is based on six replicate samples.

Date	21 August			
Station	9		10	
Location Lat.	69°07'N		69°09'N	
Long.	138°00'W		138°00'W	
Depth (m)	6.8		17.0	
Group or Species	Mean	S.D.	Mean	S.D.
HYDROZOA				
Sarsia princeps	-	-	3.49	8.54
Halitholus cirratus	23.85	58.42	117.93	182.37
Rathkea octopunctata	3.11	1.73	1.61	0.30
Euphysa flammea	1.82	4.46	39.04	40.28
Obelia sp.	P	-	0.04	0.09
? *Phialidium languidum*	-	-	0.88	1.48
? *Margelopsis hartlaubi*	1.30	3.19	-	-
Aglantha digitale	6.07	5.05	14.73	8.05
Aeginopsis laurentii	0.69	1.19	1.04	0.99
SIPHONOPHORA - unid.	-	-	0.58	1.42
CTENOPHORA - unid.	0.23	0.56	32.92	65.13
PTEROPODA				
Limacina helicina	3.37	8.25	0.08	0.12
BIVALVIA - juvenile	-	-	P	-
POLYCHAETA	P	-	0.08	0.12
ISOPODA	P	-	-	-
CIRRIPEDIA - nauplius	P	-	-	-
- cypris	-	-	P	-
OSTRACODA - Myodocopid	-	-	P	-
CALANOIDA				
Calanus glacialis	P	-	3.12	1.86
C. hyperboreus	13.96	7.96	109.31	28.55
Pseudocalanus minutus	2.30	0.57	26.73	23.72
Derjuginia tolli	1.81	0.44	15.62	14.00
Chiridius obtusifrons	-	-	0.04	0.09
Euchaeta glacialis	-	-	0.07	0.18
Limnocalanus macrurus	74.04	14.02	1.69	0.59

Appendix Table 3. Concluded.

Date	21 August			
Station	9		10	
Location Lat.	69°07'N		69°09'N	
Long.	138°00'W		138°00'W	
Depth (m)	6.8		17.0	
Group or Species	Mean	S.D.	Mean	S.D.
CALANOIDA (Cont'd)				
Metridia longa	-	-	1.78	1.27
Scolecithricella minor	-	-	P	-
Acartia longiremis	P	-	-	-
A. clausi	P	-	P	-
Unid. nauplius	P	-	-	-
AMPHIPODA				
Parathemisto abyssorum	-	-	P	-
Hyperiid juvenile	-	-	P	-
MYSIDACEA				
Mysis litoralis	45.51	15.55	42.37	41.07
Unid. (or Euphausiid?)	-	-	1.13	2.78
CHAETOGNATHA				
Sagitta elegans	2.78	1.81	5.26	4.44
Eukrohnia hamata	0.84	2.07	1.37	1.49
LARVACEA				
Oikopleura sp.	22.72	4.22	13.09	4.32
UNID. - invert. larva	-	-	-	-
TOTAL	204.38	65.30	433.98	188.46

P = <1 mg in a sample.
? = I.D. not verified.

Appendix Table 4. Biomass (mg/m^3 wet weight) of zooplankton collected in vertical tows at stations off King Point, N.W.T., 6 September 1980. Each mean and standard deviation is based on six replicate samples.

Date	6 September			
Station	9		10	
Location Lat.	69°07'N		69°09'N	
Long.	138°00'W		138°00'W	
Depth (m)	7.5		16.3	
Group or Species	Mean	S.D.	Mean	S.D.
HYDROZOA				
Rathkea octopunctata	P	-	P	-
Obelia sp.	-	-	P	-
Aglantha digitale	-	-	P	-
Aglantha(?) larvae	P	-	P	-
Aeginopsis laurentii	7.80	10.56	13.32	10.40
CTENOPHORA - unid.	0.53	1.29	0.21	0.34
NEMATODA - unid.	-	-	P	-
OLIGOCHAETA - unid.	P	-	-	-
POLYCHAETA - adult	-	-	0.16	0.33
- juvenile	-	-	P	-
- trochophore	-	-	P	-
ISOPODA	-	-	P	-
CIRRIPEDIA - cypris	-	-	P	-
- nauplius	-	-	P	-
CALANOIDA				
Calanus glacialis	0.01	0.03	0.11	0.15
Pseudocalanus minutus	P	-	P	-
Derjuginia tolli	-	-	0.01	0.02
*Limnocalanus macrurus**	2.28	2.25	0.03	0.05
Acartia longiremis	0.03	0.07	0.03	0.04
Acartia clausi	0.41	0.18	0.01	0.02
Acartia spp.	P	-	-	-
Temoridae	P	-	-	-
Nauplius	0.74	0.41	0.10	0.15
HARPACTICOIDA				
Tisbe sp.	-	-	P	-
Unid. copepodite	P	-	-	-

* = *L. m. grimaldi*.

Appendix Table 4. Concluded.

Date	6 September			
Station	9		10	
Location Lat.	69°07'N		69°09'N	
Long.	138°00'W		138°00'W	
Depth (m)	7.5		16.3	
Group or Species	Mean	S.D.	Mean	S.D.
CYCLOPINA				
Oithona similis	P	-	P	-
Cyclopina sp.	P	-	-	-
AMPHIPODA				
Onisimus sp.	-	-	0.07	0.17
Hyperiid juvenile	0.19	0.45	0.29	0.42
Oedicerotid	-	-	0.03	0.08
ECHINODERMATA				
Ophiuroid juvenile	-	-	0.01	0.02
LARVACEA				
Fritillaria borealis	P	-	P	-
Oikopleura sp.	P	-	P	-
TOTAL	11.99	10.78	14.37	10.19

P = <1 mg in sample.
? = I.D. not verified.

Appendix Table 5. Biomass (mg/m^3 wet weight) of zooplankton collected in horizontal tows at stations off King Point, N.W.T., 20 August 1980. Each mean and standard deviation is based on six replicate samples.

Date	20 August					
Station	9		10			
Location Lat.	69°07'N		69°09'N			
Long.	138°00'W		138°00'W			
Depth (m)	5.5		20.0			
Tow Depth (m)	3		3		10	
Group or Species	Mean	S.D.	Mean	S.D.	Mean	S.D.
HYDROZOA						
Sarsia princeps	47.97	90.50	23.97	58.72	-	-
Halitholus cirratus	14.44	16.76	23.64	28.53	36.50	56.58
Halitholus sp. dam.	1.20	2.93	1.49	3.65	-	-
Rathkea octopunctata	2.21	1.80	3.57	3.94	0.04	0.07
Euphysa flammea	6.61	11.49	4.45	6.28	85.69	71.72
Obelia sp.	0.17	0.31	0.19	0.24	P	-
? *Phialidium languidum*	0.44	0.96	-	-	-	-
? *Margelopsis hartlaubi*	-	-	1.60	3.91	P	-
Aglantha digitale	38.88	20.69	2.60	3.82	14.67	3.52
Aeginopsis laurentii	0.82	0.75	0.09	0.10	1.45	1.29
CTENOPHORA	1.07	2.44	1.53	1.89	8.29	11.45
PTEROPODA						
Limacina helicina	-	-	-	-	0.06	0.11
ISOPODA	P	-	-	-	-	-
CALANOIDA						
Calanus glacialis	-	-	-	-	0.34	0.43
C. hyperboreus	2.14	2.32	0.04	0.07	23.55	30.40
Pseudocalanus minutus	P	-	P	-	P	-
Derjuginia tolli	-	-	-	-	-	-
*Limnocalanus macrurus**	1.89	1.26	0.17	0.06	0.17	0.13
Euchaeta glacilis	-	-	-	-	0.23	0.34
Metridia longa	0.02	0.05	-	-	0.09	0.15
Heterorhabdus norvegicus	-	-	-	-	-	-
? *Scaphocalanus magnus*	-	-	-	-	0.13	0.21
Acartia longiremis	-	-	-	-	-	-
A. clausi	P	-	P	-	P	-
Nauplius	-	-	-	-	-	-

* = *L. m. grimaldi*.

Appendix Table 5. Concluded.

Date	20 August					
Station	9		10			
Location Lat.	69°07'N		69°09'N			
Long.	138°00'W		138°00'W			
Depth (m)	5.5		20.00			
Tow Depth (m)	3		3		10	
Group or Species	Mean	S.D.	Mean	S.D.	Mean	S.D.
CYCLOPOIDA						
*Oithona similis***	P	-	-	-	-	-
AMPHIPODA						
Parathemisto abyssorum	0.17	0.27	-	-	0.04	0.07
Hyperia galba	0.50	1.23	-	-	0.13	0.31
Hyperiid juvenile	0.02	0.05	P	-	P	-
MYSIDACEA						
Mysis litoralis	257.09	483.35	0.06	0.16	65.16	102.22
EUPHAUSIACEA						
? *Thysanoessa* sp.	-	-	-	-	0.38	0.93
DECAPODA - juvenile	3.55	6.63	-	-	1.15	1.49
CHAETOGNATHA						
Sagitta elegans	P	-	P	-	1.74	2.27
Eukrohnia hamata	0.23	0.41	-	-	0.15	0.36
LARVACEA						
Fritillaria borealis	-	-	-	-	-	-
Oikopleura sp.	2.81	3.20	0.19	0.35	4.18	1.21
PISCES						
Boreogadus saida	-	-	-	-	-	-
? *Liopsetta glacialis*	0.17	0.31	-	-	-	-
Liparis sp.	-	-	-	-	8.92	21.85
Pungitius pungitius	-	-	-	-	-	-
Lumpenus sp.	2.58	6.32	3.67	9.00	5.02	8.41
TOTAL	384.97	468.67	67.26	58.86	258.04	102.60

? = I.D. not verified.
** = smaller than mesh size therefore not representative.
P = <1 mg wet weight in sample.

Appendix Table 6. Biomass (mg/m^3 wet weight) of zooplankton collected in drop net samples at stations off King Point, N.W.T., 20 August 1980. Each mean and standard deviation is based on five replicate samples (at Station 9) or three samples (at Station 10).

Date	20 August			
Station	9		10	
Location Lat.	69°07'N		69°09'N	
Long.	138°00'W		138°00'W	
Depth (m)	6.8		17.0	
Group or Species	Mean	S.D.	Mean	S.D.
HYDROZOA				
Aeginopsis laurentii	0.40	0.55	-	-
Aglantha digitale	4.20	5.72	5.33	9.24
Euphysa flammea	38.00	51.31	21.67	20.60
Margelopsis hartlaubi	10.60	23.70	-	-
Rathkea octopunctata	-	-	P	-
Unidentified	-	-	1.67	2.89
CALANOIDA				
Calanus hyperboreus	20.00	13.45	132.67	24.01
C. glacialis	-	-	P	-
Limnocalanus macrurus*	P	-	P	-
Euchaeta glacialis	-	-	0.33	0.58
Harpacticoid	-	-	P	-
AMPHIPODA				
Parathemisto abyssorum	0.40	0.89	-	-
Boeckosimus affinis	-	-	9.33	16.17
Oedicerotid juvenile	3.00	5.66	6.00	10.39
Amphipod juvenile	-	-	P	-
MYSIDACEA				
Mysis litoralis	993.60	610.73	34.67	36.07
EUPHAUSIACEA				
Thysanoessa sp.	-	-	19.33	33.49
DECAPODA				
Decapod juvenile	-	-	P	-
ISOPODA				
Saduria entomon	239.00	187.76	190.33	329.67
CHAETOGNATHA				
Eukrohnia hamata	4.20	6.26	-	-
LARVACEA				
Oikopleura sp.	0.40	0.55	3.00	5.20
TOTAL	1313.40	-	424.34	-

* = probably subspecies grimaldi.

P = <1 mg wet weight in sample.

Appendix Table 7. Biomass (mg/m^3 wet weight) of zooplankton collected in horizontal tows at various depths at stations off Richards Island in 1981. Each mean and standard deviation is based on three replicate samples.

	L-1 (1 August)						L-1 (6 September)					
	0 m		5 m		15 m		0 m		5 m		15 m	
SPECIES	MEAN	SD	MEAN	SD	MEAN	SD	MEAN	SD	MEAN	SD	MEAN	SD
HYDROZOA												
AEGINOPSIS LAURENTII	0	0	0	0	1.021	.7115	.0609	.1055	2.837	2.599	3.333	.4389
AGLANTHA DIGITALE	0	0	0	0	6.275	1.295	0.	0	0	0	1.722	.8510
EUPHYSA FLAMMEA	0	0	0	0	8.393	5.219	.0106	.0184	0	0	0	0
HALITHOLUS CIRRATUS	.9439	1.088	0	0	97.61	29.87	2.824	4.891	16.66	26.37	12.37	14.55
HALITHOLUS PAUPER	0	0	0	0	0	0	0	0	0	0	0	0
DIMOPHYES ARCTICA	0	0	0	0	.2997	.1324	0	0	0	0	0	0
RATHKEA OCTOPUNCTATA	.0191	.0331	.1252	.1997	8.E-4	6.E-5	0	0	0	0	0	0
OBELIA SP	.0037	.0064	.01	.0102	0	0	0	0	.0024	.0041	0	0
SARSIA SPP	0	0	0	0	0	0	0	0	0	0	0	0
BOUGAINVILLEA SP	0	0	0	0	2.897	2.765	0	0	0	0	0	0
UNIDENTIFIED	0	0	0	0	7.274	2.618	0	0	0	0	0	0
CTENOPHORA												
BEROE CUCUMIS	0	0	0	0	0	0	0	0	0	0	0	0
UNIDENTIFIED	0	0	0	0	6.972	5.114	.0025	.0036	2.633	1.959	1.151	.5894
GASTROPODA												
UNIDENTIFIED	0	0	0	0	.0061	.0098	0	0	0	0	0	0
PTEROPODA												
CLIONE LIMACINA	0	0	0	0	5.E-4	5.E-4	0	0	0	0	0	0
LIMACINA HELICINA	0	0	0	0	.4900	.1241	0	0	0	0	.5824	.6900
UNIDENTIFIED	0	0	0	0	0	0	0	0	0	0	0	0
CLADOCERA												
PODON SP	0	0	7.E-4	6.E-4	0	0	0	0	0	0	0	0
CIRRIPEDIA												
UNIDENTIFIED	0	0	0	0	3.E-4	5.E-4	0	0	0	0	0	0
CALANOIDA												
CALANUS GLACIALIS	0	0	0	0	2.885	4.883	.9243	.4695	41.24	54.09	.7405	.9726
CALANUS HYPERBOREUS	.0071	.0114	0	0	24.11	37.18	.1206	.0595	1.519	1.210	.2037	.1469
PSEUDOCALANUS MINUTUS	7.E-4	6.E-4	3.E-4	6.E-4	.6010	.9860	.0132	.0051	.3178	.4499	.0076	.0112
DERJUGINIA TOLLI	0	0	0	0	.1742	.3011	.0473	.0199	.1028	.1586	.0042	.0073
METRIDIA LONGA	.0032	.0055	3.E-4	6.E-4	1.533	2.289	0	0	0	0	.0274	.0248
EUCHAETA GLACIALIS	0	0	0	0	.6138	.9015	0	0	0	0	.0750	.1300
LIMNOCALANUS MACRURUS	.0069	.0050	.0431	.0205	.4295	.5365	.0026	.0046	.2815	.4610	0	0
ACARTIA CLAUSI	.0010	6.E-5	3.E-4	6.E-4	3.E-4	4.E-4	0	0	0	0	0	0
ACARTIA LONGIREMIS	0	0	0	0	5.E-4	5.E-4	.0032	.0041	0	0	0	0
EURYTEMORA SP	3.E-4	6.E-4	.0032	.0055	0	0	.0025	.0036	2.E-4	4.E-4	0	0
SCAPHOCALANUS SP	0	0	0	0	0	0	0	0	0	0	0	0
UNIDENTIFIED	.0034	.0058	0	0	0	0	0	0	0	0	0	0
MYSIDAE												
MYSIS LITORALIS	0	0	0	0	0	0	0	0	0	0	0	0
MYSIS RELICTA	0	0	0	0	0	0	0	0	0	0	0	0
UNIDENTIFIED	0	0	0	0	0	0	0	0	0	0	0	0
EUPHAUSIIDAE												
THYSANOESSA SPP	0	0	0	0	0	0	0	0	0	0	0	0
ISOPODA												
UNIDENTIFIED	0	0	0	0	0	0	0	0	0	0	0	0
AMPHIPODA												
APHERUSA GLACIALIS	0	0	0	0	3.066	2.818	.0577	.0366	3.185	5.479	.4327	.4211
ONISIMUS GLACIALIS	0	0	0	0	2.066	1.976	0	0	0	0	1.022	.5819
ONISIMUS NANSENI	0	0	0	0	0	0	0	0	0	0	0	0
BOECKOSIMUS SP	0	0	0	0	0	0	0	0	0	0	0	0
GAMMARUS SETOSUS	0	0	0	0	0	0	0	0	.0076	.0132	0	0
GAMMARIDEA JUV	0	0	0	0	0	0	0	0	.0281	.0481	.0328	.0482
HYPERIA GALBA	0	0	0	0	.8743	.2043	0	0	.0325	.0564	.0834	.0963
PARATHEMISTO ABYSSORUM	0	0	0	0	.0164	.0143	0	0	.1870	.2418	.2152	.1954
PARATHEMISTO LIBELLULA	0	0	0	0	.0668	.1157	0	0	1.125	.8120	5.642	5.867
HYPERIA JUV	0	0	0	0	.0313	.0335	2.E-4	4.E-4	.0188	.0320	.0068	.0119
DECAPODA												
UNIDENTIFIED	0	0	0	0	.5359	.4587	0	0	.0996	.0963	2.037	3.022
ASTEROIDEA												
UNIDENTIFIED	0	0	0	0	5.E-4	5.E-4	0	0	0	0	0	0
CHAETOGNATHA												
SAGITTA ELEGANS	0	0	0	0	2.242	2.322	0	0	0	0	.0696	.1036
LARVACEA												
OIKOPLEURA VANHOEFFENI	1.667	3.233	.4708	.8154	55.69	64.47	1.159	1.206	84.40	123.9	63.67	30.63
PISCES												
GADIDAE YOY	.1694	.2934	.2136	.3348	68.61	39.09	0	0	.6519	1.006	3.381	3.579
STICHAEIDAE YOY	0	0	0	0	.2826	.4894	0	0	0	0	0	0
LIPARIDAE YOY	0	0	0	0	.5283	.4964	0	0	0	0	0	0
COTTIDAE YOY	0	0	0	0	0	0	0	0	0	0	.4115	.3704
PLEURONECTIDAE YOY	0	0	0	0	0	0	0	0	5.E-4	8.E-4	0	0
DEBRIS COPEPOD EXUVIAE	0	0	0	0	0	0	.2427	.2057	0	0	4.305	7.456
SUMMARY												
HYDROZOA	.9667	1.077	.1352	.2089	123.8	36.06	2.895	4.830	19.50	28.95	17.43	15.19
COPEPODS	.0225	.0201	.0473	.0232	30.35	47.07	1.114	.4343	43.46	56.11	1.058	1.073
AMPHIPODS	0	0	0	0	6.123	4.095	.0579	.0364	4.584	5.732	7.435	6.804
OTHERS	2.034	3.527	.6851	1.150	135.4	70.83	1.404	1.165	87.78	126.9	75.61	36.46
TOTALS	3.025	2.771	.8675	1.372	295.6	71.97	5.471	4.209	155.3	217.2	101.5	49.36

	N-10 (19 August)						N-8 (14 August)	
	0 m		5 m		15 m		0 m	
SPECIES	MEAN	SD	MEAN	SD	MEAN	SD	MEAN	SD
HYDROZOA								
AEGINOPSIS LAURENTII	.0170	.0184	1.376	.9201	1.481	1.489	0	0
AGLANTHA DIGITALE	0	0	1.202	.9961	25.37	30.74	0	0
EUPHYSA FLAMMEA	0	0	0	0	7.431	12.62	.0798	.3371
HALITHOLUS CIRRATUS	1.376	1.957	2.732	2.673	21.24	25.69	.8065	1.397
HALITHOLUS PAUPER	0	0	0	0	0	0	0	0
DIMOPHYES ARCTICA	0	0	0	0	0	0	0	0
RATHKEA OCTOPUNCTATA	0	0	8.E-4	7.E-4	0	0	4.E-4	6.E-4
OBELIA SP	.0144	.0124	.0450	.0286	0	0	.0195	.0080
SARSIA SPP	0	0	0	0	1.739	2.594	0	0
BOUGAINVILLEA SP	0	0	0	0	0	0	0	0
UNIDENTIFIED	0	0	0	0	0	0	0	0
CTENOPHORA								
BEROE CUCUMIS	0	0	0	0	0	0	0	0
UNIDENTIFIED	4.803	6.897	.2645	.1927	25.21	36.00	9.207	4.455
GASTROPODA								
UNIDENTIFIED	0	0	0	0	.0172	.0298	0	0
PTEROPODA								
CLIONE LIMACINA	0	0	1.800	3.096	.0229	.0397	0	0
LIMACINA HELICINA	.0388	.0400	0	0	.5711	.6480	0	0
UNIDENTIFIED	0	0	0	0	0	0	0	0
CLADOCERA								
PODON SP	.0055	.0079	3.E-4	5.E-4	0	0	.0044	.0056
CIRRIPEDIA								
UNIDENTIFIED	0	0	.0010	2.E-4	3.E-4	5.E-4	8.E-4	7.E-4
CALANOIDA								
CALANUS GLACIALIS	.2955	.2344	.6116	.4944	50.11	66.36	7.659	5.017
CALANUS HYPERBOREUS	1.885	3.177	.1610	.1498	572.7	532.1	.0123	.0133
PSEUDOCALANUS MINUTUS	.0466	.0174	.0452	.0189	2.036	3.397	.2072	.1861
DERJUGINIA TOLLI	0	0	0	0	.3055	.5292	0	0
METRIDIA LONGA	0	0	4.E-4	7.E-4	3.380	5.414	0	0
EUCHAETA GLACIALIS	0	0	0	0	0	0	0	0
LIMNOCALANUS MACRURUS	.0211	.0189	.0309	.0190	0	0	.4323	.1023
ACARTIA CLAUSI	.0592	.0476	3.E-4	5.E-4	0	0	.0082	.0065
ACARTIA LONGIREMIS	.0066	.0102	4.E-4	6.E-4	3.E-4	5.E-4	0	0
EURYTEMORA SP	0	0	0	0	.0042	.0073	.0149	.0237
SCAPHOCALANUS SP	0	0	0	0	0	0	0	0
UNIDENTIFIED	0	0	0	0	0	0	0	0
MYSIDAE								
MYSIS LITORALIS	0	0	0	0	.3305	.5724	0	0
MYSIS RELICTA	0	0	0	0	0	0	0	0
UNIDENTIFIED	0	0	0	0	0	0	0	0
EUPHAUSIIDAE								
THYSANOESSA SPP	0	0	0	0	5.130	7.766	0	0
ISOPODA								
UNIDENTIFIED	0	0	0	0	0	0	0	0
AMPHIPODA								
APHERUSA GLACIALIS	0	0	0	0	7.125	6.742	0	0
ONISIMUS GLACIALIS	0	0	0	0	1.390	2.212	0	0
ONISIMUS NANSENI	0	0	0	0	0	0	0	0
BOECKOSIMUS SP	0	0	0	0	0	0	0	0
GAMMARUS SETOSUS	0	0	0	0	0	0	0	0
GAMMARIDEA JUV	0	0	0	0	0	0	0	0
HYPERIA GALBA	0	0	.0107	.0186	.3132	.4269	0	0
PARATHEMISTO ABYSSORUM	0	0	.0204	.0105	1.902	2.690	0	0
PARATHEMISTO LIBELLULA	0	0	.0486	.0842	8.712	8.123	0	0
HYPERIA JUV	0	0	.0151	.0159	.0119	.0195	0	0
DECAPODA								
UNIDENTIFIED	.0731	.1265	.2546	.4318	.2775	.2403	0	0
ASTEROIDEA								
UNIDENTIFIED	0	0	0	0	0	0	0	0
CHAETOGNATHA								
SAGITTA ELEGANS	.0061	.0105	.0990	.1458	5.465	5.538	.0040	.0057
LARVACEA								
OIKOPLEURA VANHOEFFENI	.1751	.1343	.0358	.0439	63.60	61.87	0	0
PISCES								
GADIDAE YOY	0	0	1.789	.3983	3.907	4.845	0	0
STICHAEIDAE YOY	0	0	1.012	1.753	0	0	0	0
LIPARIDAE YOY	0	0	0	0	.2667	.4620	0	0
COTTIDAE YOY	0	0	0	0	0	0	0	0
PLEURONECTIDAE YOY	5.E-4	8.E-4	0	0	0	0	0	0
DEBRIS COPEPOD EXUVIAE	10.04	1.036	2.058	.5395	47.89	45.72	0	0
SUMMARY								
HYDROZOA	1.407	1.956	5.357	4.535	57.26	72.73	1.106	1.287
COPEPODS	2.314	3.485	.8508	.6416	628.6	598.0	6.334	5.286
AMPHIPODS	0	0	.0948	.0763	19.45	17.12	0	0
OTHERS	15.14	6.788	7.314	2.959	152.7	126.4	9.216	4.450
TOTALS	18.86	9.738	13.62	7.795	856.0	790.0	16.66	2.396

Appendix Table 7. Continued.

	No whales						Whales					
	L-1 (11 August)						N-9 (18/19 August)					
SPECIES	0 m		5 m		10 m		0 m		15 m		2 m	
	MEAN	SD	MEAN	SD	MEAN	SD	MEAN	SD	MEAN	SD	MEAN	SD
HYDROZOA												
AEGINOPSIS LAURENTII	0	0	.3148	.0711	1.773	1.628	.1793	.1010	.5924	.7847	.4937	.5131
AGLANTHA DIGITALE	0	0	0	0	56.67	29.50	.5808	.4977	19.97	22.41	.9027	.4409
EUPHYSA FLAMMEA	.0678	.1174	.3869	.3685	16.25	4.554	.5747	.9953	8.013	13.86	.1308	.1203
HALITHOLUS CIRRATUS	.6043	1.047	51.83	40.29	48.02	41.53	5.821	5.544	18.46	18.93	5.151	6.823
HALITHOLUS PAUPER	0	0	0	0	.0241	.0338	0	0	0	0	0	0
DIMOPHYES ARCTICA	0	0	0	0	0	0	0	0	0	0	0	0
RATHKEA OCTOPUNCTATA	0	0	.0125	.0127	.0449	.0307	.0210	.0180	.0046	.0060	.0010	2.E-4
OBELIA SP	.0044	.0056	.0161	.0088	0	0	.1127	.0110	0	0	.1176	.0578
SARSIA SPP	0	0	0	0	14.30	11.64	0	0	.9478	.8850	.8585	1.114
BOUGAINVILLEA SP	0	0	0	0	8.448	4.055	0	0	0	0	0	0
UNIDENTIFIED	0	0	0	0	0	0	0	0	0	0	0	0
CTENOPHORA												
BEROE CUCUMIS	0	0	0	0	0	0	6.519	4.300	0	0	2.420	4.192
UNIDENTIFIED	.3546	.6142	.4351	.3006	11.09	3.925	0	0	10.88	15.37	4.953	4.631
GASTROPODA												
UNIDENTIFIED	0	0	0	0	.0118	.0096	0	0	.0800	.1386	0	0
PTEROPODA												
CLIONE LIMACINA	0	0	0	0	.0320	.0189	.0105	.0182	.0622	.1077	0	0
LIMACINA HELICINA	0	0	.0788	.0695	2.113	1.315	.1878	.1298	1.838	1.177	1.343	.6488
UNIDENTIFIED	0	0	0	0	0	0	0	0	0	0	0	0
CLADOCERA												
PODON SP	.5884	.6673	.0321	.0357	6.E-4	5.E-4	.0038	.0058	0	0	.0124	.0097
CIRRIPEDIA												
UNIDENTIFIED	0	0	0	0	3.E-4	5.E-4	3.E-4	6.E-4	0	0	0	0
CALANOIDA												
CALANUS GLACIALIS	.0191	.0145	1.994	1.670	4.104	.3316	48.96	25.94	77.04	39.91	30.10	3.029
CALANUS HYPERBOREUS	.0218	.0358	1.299	1.103	40.54	4.671	148.0	67.35	616.8	106.5	26.15	2.461
PSEUDOCALANUS MINUTUS	.0158	.0180	3.225	2.579	47.35	51.66	2.405	1.360	3.917	3.395	.3757	.2836
DERJUGINIA TOLLI	0	0	0	0	11.89	18.44	0	0	.0800	.1386	0	0
METRIDIA LONGA	0	0	.0044	.0076	.1223	.1658	0	0	2.403	4.156	.0029	.0051
EUCHAETA GLACIALIS	0	0	0	0	.1750	.1787	0	0	0	0	0	0
LIMNOCALANUS MACRURUS	1.631	1.544	.3238	.2411	2.541	3.377	.0140	.0160	0	0	.0032	.0048
ACARTIA CLAUSI	.1512	.0871	.0377	.0642	0	0	.1070	.1400	0	0	.0129	.0042
ACARTIA LONGIREMIS	0	0	0	0	0	0	.0035	.0060	0	0	3.E-4	5.E-4
EURYTEMORA SP	.0055	.0067	.0078	.0069	0	0	.0105	.0105	.0231	.0400	.0246	.0275
SCAPHOCALANUS SP	0	0	0	0	0	0	0	0	0	0	0	0
UNIDENTIFIED	0	0	0	0	0	0	0	0	0	0	0	0
MYSIDAE												
MYSIS LITORALIS	0	0	0	0	6.004	8.738	0	0	4.675	3.546	0	0
MYSIS RELICTA	0	0	0	0	.0063	.0109	0	0	0	0	0	0
UNIDENTIFIED	0	0	0	0	0	0	0	0	0	0	0	0
EUPHAUSIIDAE												
THYSANOESSA SPP	0	0	.0131	.0227	5.787	3.104	0	0	3.091	1.722	0	0
ISOPODA												
UNIDENTIFIED	0	0	0	0	3.E-4	5.E-4	0	0	0	0	0	0
AMPHIPODA												
APHERUSA GLACIALIS	0	0	0	0	.0090	.0155	.0385	.0318	3.433	5.070	.0089	.0088
ONISIMUS GLACIALIS	0	0	0	0	0	0	0	0	.0280	.0485	0	0
ONISIMUS NANSENI	0	0	0	0	0	0	0	0	.3321	.5752	0	0
BOECKOSIMUS SP	0	0	0	0	0	0	0	0	0	0	0	0
GAMMARUS SETOSUS	0	0	0	0	0	0	0	0	0	0	0	0
GAMMARIDEA JUV	0	0	0	0	3.E-4	5.E-4	4.E-4	6.E-4	0	0	0	0
HYPERIA GALBA	0	0	.0175	.0303	1.223	.8886	.5359	.1438	.3551	.4701	.1654	.1331
PARATHEMISTO ABYSSORUM	0	0	.0127	.0131	.2543	.0102	.1267	.1097	2.994	4.436	.1125	.0751
PARATHEMISTO LIBELLULA	0	0	0	0	.0794	.0729	0	0	1.421	.6462	0	0
HYPERIA JUV	0	0	.0034	.0059	.0173	.0088	.0105	.0182	.0046	.0080	7.E-4	6.E-4
DECAPODA												
UNIDENTIFIED	0	0	.0080	.0138	1.563	.9241	0	0	.5440	.3849	.6341	.8490
ASTEROIDEA												
UNIDENTIFIED	0	0	0	0	0	0	0	0	0	0	0	0
CHAETOGNATHA												
SAGITTA ELEGANS	0	0	.1312	.1310	7.162	5.429	.0145	.0156	5.925	6.711	.0046	.0065
LARVACEA												
OIKOPLEURA VANHOEFFENI	0	0	0	0	0	0	1.860	1.644	79.11	69.32	.1256	.1130
PISCES												
GADIDAE YOY	0	0	0	0	5.423	4.963	0	0	4.268	5.918	.2304	.3990
STICHAEIDAE YOY	0	0	0	0	.8332	1.443	0	0	0	0	.0121	.0210
LIPARIDAE YOY	0	0	0	0	.3725	.6452	0	0	.5812	1.007	.5574	.7473
COTTIDAE YOY	0	0	0	0	0	0	0	0	0	0	0	0
• PLEURONECTIDAE YOY	0	0	0	0	0	0	0	0	0	0	0	0
DEBRIS COPEPOD EXUVIAE	0	0	0	0	0	0	0	0	17.79	20.65	0	0
SUMMARY												
HYDROZOA	.6764	.9988	52.56	40.24	145.5	83.60	7.289	4.349	47.99	36.80	7.655	8.768
COPEPODS	1.845	1.586	6.891	4.914	106.7	77.23	199.5	79.84	700.2	143.8	56.67	.4120
AMPHIPODS	0	0	.0336	.0390	1.584	.9055	.7119	.2536	8.568	10.90	.2876	.0705
OTHERS	.9430	1.281	.6982	.1406	40.40	9.941	8.596	6.014	128.8	89.88	10.29	4.492
TOTALS	3.464	3.856	60.18	45.08	294.2	41.02	216.1	85.95	685.6	267.5	74.91	13.58

	Whales						No whales					
	N-11 (24 August)						N-12 (24 August)					
SPECIES	0 m		5 m		15 m		0 m		5 m		15 m	
	MEAN	SD	MEAN	SD	MEAN	SD	MEAN	SD	MEAN	SD	MEAN	SD
HYDROZOA												
AEGINOPSIS LAURENTII	.1460	.2409	1.536	1.568	2.523	1.401	0	0	.0178	.0308	.3297	.2382
AGLANTHA DIGITALE	.3890	.4344	.5011	.2718	7.979	3.536	.2711	.2361	.0468	.0811	3.039	3.440
EUPHYSA FLAMMEA	1.219	1.554	.2090	.1890	2.599	1.220	.1319	.1363	.0301	.0522	.0989	.1714
HALITHOLUS CIRRATUS	4.492	3.976	9.886	14.61	88.92	66.47	1.439	1.648	6.829	7.313	29.54	37.74
HALITHOLUS PAUPER	0	0	0	0	0	0	0	0	0	0	0	0
DIMOPHYES ARCTICA	0	0	0	0	0	0	0	0	0	0	0	0
RATHKEA OCTOPUNCTATA	0	0	0	0	0	0	0	0	0	0	0	0
OBELIA SP	0	0	.0120	.0208	0	0	3.E-4	6.E-4	0	0	0	0
SARSIA SPP	0	0	0	0	2.068	2.093	.0309	.0535	0	0	3.251	4.239
BOUGAINVILLEA SP	0	0	0	0	0	0	0	0	0	0	0	0
UNIDENTIFIED	0	0	.1736	.2843	3.E-4	5.E-4	0	0	0	0	0	0
CTENOPHORA												
BEROE CUCUMIS	0	0	0	0	0	0	0	0	0	0	0	0
UNIDENTIFIED	84.77	15.85	10.21	1.280	65.23	62.48	12.82	6.509	8.972	2.455	13.57	7.410
GASTROPODA												
UNIDENTIFIED	0	0	0	0	.0830	.1438	0	0	0	0	0	0
PTEROPODA												
CLIONE LIMACINA	0	0	.0074	.0129	.0266	.0294	.0094	.0163	0	0	0	0
LIMACINA HELICINA	.0234	.0406	.0980	.1093	5.717	.8893	0	0	.0571	.0205	.1659	.2653
UNIDENTIFIED	0	0	0	0	0	0	0	0	0	0	0	0
CLADOCERA												
PODON SP	7.E-4	.0012	0	0	0	0	0	0	0	0	0	0
CIRRIPEDIA												
UNIDENTIFIED	0	0	4.E-4	6.E-4	0	0	0	0	0	0	0	0
CALANOIDA												
CALANUS GLACIALIS	455.1	665.4	20.19	15.65	165.1	47.49	18.59	3.123	35.05	12.58	186.8	52.88
CALANUS HYPERBOREUS	.4373	.3339	1.110	1.563	738.1	561.2	.4042	.4462	1.540	.8916	16.22	24.10
PSEUDOCALANUS MINUTUS	4.937	4.080	3.440	4.538	.4792	.3620	14.57	13.92	1.102	.4933	4.901	5.650
DERJUGINIA TOLLI	0	0	0	0	0	0	0	0	0	0	.0761	.1318
METRIDIA LONGA	0	0	.0036	.0052	0	0	0	0	0	0	.1355	.2346
EUCHAETA GLACIALIS	0	0	0	0	.3321	.5752	0	0	0	0	0	0
LIMNOCALANUS MACRURUS	0	0	0	0	0	0	1.178	.3680	1.224	.7208	.9457	.5125
ACARTIA CLAUSI	7.E-4	.0012	0	0	0	0	.0103	10E-4	.0033	.0049	0	0
ACARTIA LONGIREMIS	.0012	.0011	8.E-4	7.E-4	0	0	7.E-4	6.E-4	3.E-4	6.E-4	0	0
EURYTEMORA SP	.0071	.0122	4.E-4	6.E-4	0	0	.0035	.0051	0	0	.0677	.1173
SCAPHOCALANUS SP	0	0	0	0	0	0	0	0	0	0	0	0
UNIDENTIFIED	0	0	0	0	0	0	0	0	0	0	0	0
MYSIDAE												
MYSIS LITORALIS	0	0	0	0	0	0	0	0	.0226	.0395	247.9	104.8
MYSIS RELICTA	0	0	0	0	0	0	0	0	0	0	0	0
UNIDENTIFIED	0	0	0	0	0	0	0	0	0	0	0	0
EUPHAUSIIDAE												
THYSANOESSA SPP	0	0	0	0	2.056	1.880	0	0	0	0	.0381	.0659
ISOPODA												
UNIDENTIFIED	0	0	0	0	0	0	0	0	0	0	3.E-4	4.E-4
AMPHIPODA												
APHERUSA GLACIALIS	.4561	.4016	.0759	.1315	48.63	78.32	.0157	.0271	.0423	.0520	.1885	.1834
ONISIMUS GLACIALIS	0	0	0	0	1.893	3.214	0	0	0	0	0	0
ONISIMUS NANSENI	0	0	0	0	0	0	0	0	0	0	0	0
BOECKOSIMUS SP	0	0	0	0	0	0	0	0	0	0	0	0
GAMMARUS SETOSUS	0	0	0	0	0	0	0	0	0	0	0	0
GAMMARIDEA JUV	0	0	4.E-4	6.E-4	.0405	.0525	0	0	0	0	0	0
HYPERIA GALBA	0	0	.0938	.1053	.7938	.5347	.0031	.0054	0	0	.1991	.2709
PARATHEMISTO ABYSSORUM	.0399	.0205	.1755	.1077	1.930	2.173	0	0	.0100	.0174	.1513	.2052
PARATHEMISTO LIBELLULA	0	0	.4505	.5971	102.4	26.74	0	0	0	0	.4807	.2295
HYPERIA JUV	.0047	.0081	.0109	.0012	.0291	.0231	0	0	0	0	.0072	.0076
DECAPODA												
UNIDENTIFIED	0	0	.4054	.2111	1.671	1.159	0	0	0	0	.2739	.1167
ASTEROIDEA												
UNIDENTIFIED	0	0	0	0	.0139	.0240	0	0	0	0	0	0
CHAETOGNATHA												
SAGITTA ELEGANS	5.E-4	8.E-4	.1143	.1139	10.61	8.087	.2531	.0681	6.093	1.111	7.231	1.081
LARVACEA												
OIKOPLEURA VANHOEFFENI	.0375	.0325	2.009	2.842	151.0	212.7	.2038	.0242	.0534	.0320	0	0
PISCES												
GADIDAE YOY	.1340	.1204	3.705	3.754	.7934	.7175	0	0	0	0	11.19	8.634
STICHAEIDAE YOY	0	0	0	0	0	0	0	0	2.215	2.013	3.772	3.267
LIPARIDAE YOY	0	0	.3278	.5677	1.122	1.944	0	0	0	0	.3349	.5800
COTTIDAE YOY	0	0	0	0	0	0	0	0	0	0	0	0
PLEURONECTIDAE YOY	.0094	.0162	.0120	.0208	0	0	0	0	0	0	0	0
DEBRIS COPEPOD EXUVIAE	.2062	.3572	0	0	3.298	5.712	0	0	0	0	0	0
SUMMARY												
HYDROZOA	6.246	4.681	12.32	14.12	104.1	70.39	1.873	1.818	6.924	7.433	36.26	45.50
COPEPODS	460.4	669.6	24.75	20.00	904.0	514.3	34.76	16.50	38.92	13.03	209.1	79.71
AMPHIPODS	.5008	.4195	.8071	.8102	155.7	81.97	.0168	.0325	.0524	.0689	1.027	.4545
OTHERS	85.18	16.17	16.89	5.914	241.6	276.6	13.29	6.563	17.41	2.945	284.4	110.7
TOTALS	552.4	673.9	54.77	15.79	1405.	936.8	49.93	21.42	63.31	11.39	530.8	181.1

Appendix Table 8. Biomass (mg/m^3 wet weight) of zooplankton collected in horizontal tows at 10 m depth at Station N-13, 25 August 1981.

	N-13 (25 August)		
SPECIES	10 m		
HYDROZOA	WT/M3	WT/M3	WT/M3
AEGINOPSIS LAURENTII	.2016	9.E-4	.1926
AGLANTHA DIGTALE	4.452	4.403	1.954
EUPHYSA FLAMMEA	1.075	2.214	1.790
HALITHOLUS CIRRATUS	114.4	88.68	45.05
HALITHOLUS PAUPER	0	0	0
DIMOPHYES ARCTICA	0	0	0
RATHKEA OCTOPUNCTATA	0	0	0
OBELIA SP	0	0	0
SARSIA SPP	15.13	4.386	1.541
UNIDENTIFIED	0	0	0
CTENOPHORA			
BEROE CUCUMIS	0	0	0
UNIDENTIFIED	3.208	3.647	6.455
GASTROPODA			
UNIDENTIFIED	0	0	0
PTEROPODA			
CLIONE LIMACINA	0	0	0
LIMACINA HELICINA	0	0	0
UNIDENTIFIED	8.E-4	0	0
CLADOCERA			
PODON SP	0	0	0
CIRRIPEDIA			
UNIDENTIFIED	0	0	0
CALANOIDA			
CALANUS GLACIALIS	15.87	46.34	34.39
CALANUS HYPERBOREUS	44.77	338.6	80.17
PSEUDOCALANUS MINUTUS	5.795	8.582	4.279
DERJUGINIA TOLLI	1.512	5.149	2.140
METRIDIA LONGA	.2520	.4291	0
LIMNOCALANUS MACRURUS	.5039	131.3	37.09
ACARTIA CLAUSI	0	0	0
ACARTIA LONGIREMIS	0	0	0
EURYTEMORA SP	0	0	0
SCAPHOCALANUS SP	0	0	0
UNIDENTIFIED	0	.4291	0
MYSIDAE			
MYSIS LITORALIS	0	157.6	.2568
MYSIS RELICTA	0	0	0
UNIDENTIFIED	0	.0086	0
EUPHAUSIIDAE			
THYSANOESSA SPP	0	0	0
ISOPODA			
UNIDENTIFIED	0	0	0
AMPHIPODA			
APHERUSA GLACIALIS	.0840	1.648	.4065
ONISIMUS GLACIALIS	0	0	0
ONISIMUS NANSENI	0	0	0
BOECKOSIMUS SP	0	.0687	0
GAMMARUS SETOSUS	0	0	0
GAMMARIDEA JUV	0	.0429	0
HYPERIA GALBA	1.218	1.056	.2710
PARATHEMISTO ABYSSORUM	.0672	.0429	.0357
PARATHEMISTO LIBELLULA	0	.4549	.2710
HYPERIA JUV	0	0	0
DECAPODA			
UNIDENTIFIED	.0168	0	0
ASTEROIDEA			
UNIDENTIFIED	0	0	0
CHAETOGNATHA			
SAGITTA ELEGANS	2.654	6.986	2.753
LARVACEA			
OIKOPLEURA VANHOEFFENI	0	0	0
PISCES			
GADIDAE YOY	0	5.192	0
STICHAEIDAE YOY	0	0	0
LIPARIDAE YOY	0	0	0
COTTIDAE YOY	0	0	0
PLEURONECTIDAE YOY	0	0	0
DEBRIS COPEPOD EXUVIAE	1.075	0	2.133
SUMMARY			
HYDROZOA	135.3	99.68	50.52
COPEPODS	68.70	530.8	158.1
AMPHIPODS	1.369	3.313	.9842
OTHERS	6.955	173.4	11.60
TOTALS	212.3	807.2	221.2

Appendix Table 9. Biomass (mg/m^3 wet weight) of zooplankton collected at various depths at stations off Richards Island and Tuktoyaktuk in 1981. Each mean and standard deviation is based on three replicate samples.

N-6 (11 August)

GROUP	0 m		15 m		20 m	
	MEAN	SD	MEAN	SD	MEAN	SD
HYDROZOA	0	0	44.08	33.49	104.4	44.53
CTENOPORA	0	0	.0808	.0079	3.137	1.845
PTEROPODA	6.E-4	10E-4	.0059	.0102	.1958	.0964
CLADOCERA	.0504	.0373	0	0	0	0
OSTRACODA	0	0	0	0	.0028	.0048
ISOPODA	0	0	0	0	0	0
CALANOIDA	3.130	5.123	22.66	18.52	94.30	60.60
MYSIDAE	0	0	0	0	0	0
EUPHAUSIIDAE	.2485	.4304	0	0	0	0
AMPHIPODA	.0552	.0956	.0621	.0580	.7580	.7230
DECAPODA	0	0	.0648	.1122	1.015	.6209
LARVACEA	0	0	0	0	0	0
CHAETOGNATHA	.0166	.0287	.1709	.2732	.6668	.4660
PISCES	0	0	.5618	.8248	4.749	4.874
BENTHIC LARVAE	0	0	0	0	0	0
DEBRIS	.5359	.2775	.0573	.0993	.4804	.8320
	0	0	0	0	0	0
SUMMARY	0	0	0	0	0	0
HYDROZOA	0	0	44.08	33.49	104.4	44.53
COPEPODS	3.130	5.123	22.66	18.52	94.30	60.60
AMPHIPODS	.0552	.0956	.0621	.0580	.7580	.7230
OTHER	.8519	.7466	.9416	.6896	10.25	7.197

N-5 (11 August)

GROUP	0 m		20 m		30 m	
	MEAN	SD	MEAN	SD	MEAN	SD
HYDROZOA	0	0	72.21	29.22	29.65	4.827
CTENOPORA	0	0	9.153	9.565	2.450	1.060
PTEROPODA	0	0	1.503	.0315	.8265	.6189
CLADOCERA	.0205	.0071	0	0	0	0
OSTRACODA	0	0	.0172	.0225	.0198	.0195
ISOPODA	0	0	0	0	.1593	.2759
CALANOIDA	.4543	.1534	394.9	273.2	274.0	174.4
MYSIDAE	0	0	.1265	.1131	.5828	.4047
EUPHAUSIIDAE	0	0	.0052	.0090	1.917	2.529
AMPHIPODA	8.E-4	7.E-4	.7929	.1493	2.523	1.338
DECAPODA	0	0	1.136	.4981	.6663	.4996
LARVACEA	0	0	.1282	.2220	0	0
CHAETOGNATHA	0	0	1.324	.5413	1.860	1.021
PISCES	0	0	3.536	1.560	.0767	.1328
BENTHIC LARVAE	0	0	.0145	.0132	2.E-4	4.E-4
DEBRIS	0	0	.4782	.5313	.6393	.5673
SUMMARY						
HYDROZOA	0	0	72.21	29.22	29.65	4.827
COPEPODS	.4543	.1534	394.9	273.2	274.0	174.4
AMPHIPODS	8.E-4	7.E-4	.7929	.1493	2.523	1.338
OTHER	.0205	.0071	17.42	9.586	9.198	2.948

N-7 (11 August)

GROUP	0 m		15 m		20 m	
	MEAN	SD	MEAN	SD	MEAN	SD
HYDROZOA	.0755	.1124	501.0	108.0	76.72	11.79
CTENOPORA	.2023	.3504	1.208	1.303	22.54	7.247
PTEROPODA	0	0	1.464	1.028	.9457	.4554
CLADOCERA	.2275	.0428	0	0	0	0
OSTRACODA	0	0	0	0	3.E-4	5.E-4
ISOPODA	0	0	0	0	0	0
CALANOIDA	.9426	.1329	54.99	66.62	142.6	82.62
MYSIDAE	0	0	0	0	.2074	.0566
EUPHAUSIIDAE	0	0	0	0	4.320	.6913
AMPHIPODA	4.E-4	6.E-4	3.611	1.678	.0933	.0926
DECAPODA	0	0	3.021	1.809	.2516	.1123
LARVACEA	0	0	0	0	0	0
CHAETOGNATHA	0	0	4.875	2.974	4.802	1.068
PISCES	.1200	.2078	4.543	1.050	0	0
BENTHIC LARVAE	0	0	.0034	.0059	3.E-4	5.E-4
DEBRIS	.3142	.4143	6.225	10.78	3.357	2.101
	0	0	0	0	0	0
SUMMARY	0	0	0	0	0	0
HYDROZOA	.0755	.1124	501.0	108.0	76.72	11.79
COPEPODS	.9426	.1329	54.99	66.62	142.6	82.62
AMPHIPODS	4.E-4	6.E-4	3.611	1.678	.0933	.0926
OTHER	.8640	.7088	21.34	13.35	36.43	7.412

N-1 (31 July)

GROUP	0 m		5 m		10 m	
	MEAN	SD	MEAN	SD	MEAN	SD
HYDROZOA	1.528	2.252	.2108	.2538	51.30	88.75
CTENOPORA	0	0	0	0	2.941	5.094
PTEROPODA	0	0	0	0	1.990	3.446
CLADOCERA	6.E-4	5.E-4	7.E-4	6.E-4	3.E-4	5.E-4
OSTRACODA	0	0	0	0	0	0
ISOPODA	0	0	0	0	0	0
CALANOIDA	.0294	.0175	.1728	.2197	3.963	6.759
MYSIDAE	0	0	0	0	0	0
EUPHAUSIIDAE	0	0	0	0	0	0
AMPHIPODA	0	0	0	0	.3402	.5892
DECAPODA	0	0	0	0	.0963	.1668
LARVACEA	0	0	0	0	0	0
CHAETOGNATHA	0	0	0	0	.0753	.1304
PISCES	0	0	.0416	.0365	2.854	4.943
BENTHIC LARVAE	3.E-4	5.E-4	.0035	.0051	3.E-4	5.E-4
DEBRIS	0	0	0	0	0	0
	0	0	0	0	0	0
SUMMARY	0	0	0	0	0	0
HYDROZOA	1.528	2.252	.2108	.2538	51.30	88.75
COPEPODS	.0294	.0175	.1728	.2197	3.963	6.759
AMPHIPODS	0	0	0	0	.3402	.5892
OTHER	9.E-4	9.E-4	.0458	.0377	7.957	13.78

Appendix Table 9. Continued.

GROUP	N-1 (12 August)				N-4 (10 August)	
	0 m		5 m		0 m	
	MEAN	SD	MEAN	SD	MEAN	SD
HYDROZOA	1.548	1.383	1.378	1.936	0	0
CTENOPORA	.6031	.7804	2.149	1.946	0	0
PTEROPODA	0	0	0	0	0	0
CLADOCERA	.6114	.1536	.2611	.3434	.0024	.0041
OSTRACODA	0	0	0	0	0	0
ISOPODA	0	0	0	0	0	0
CALANOIDA	.8462	.3954	3.538	2.235	.1033	.0550
MYSIDAE	0	0	.2632	.4559	0	0
EUPHAUSIIDAE	0	0	0	0	0	0
AMPHIPODA	0	0	0	0	0	0
DECAPODA	0	0	0	0	0	0
LARVACEA	0	0	0	0	0	0
CHAETOGNATHA	0	0	0	0	0	0
PISCES	0	0	0	0	.4455	.4904
BENTHIC LARVAE	.6222	.3700	.1287	.2230	0	0
DEBRIS	0	0	0	0	0	0
	0	0	0	0	0	0
SUMMARY	0	0	0	0	0	0
HYDROZOA	1.548	1.383	1.378	1.936	0	0
COPEPODS	.8462	.3954	3.538	2.235	.1033	.0550
AMPHIPODS	0	0	0	0	0	0
OTHER	1.837	.9773	2.802	1.778	.4479	.4898

The reader is referred to the 'Project Rationale, Design and Summary' section of this report (p. 1-32) for a summary of the work.