ARCTIC
VOL. 42, NO. 1 (MARCH 1989) P. 24-30

Observations on the Ice-Breaking and Ice Navigation Behavior of Migrating Bowhead Whales (*Balaena mysticetus*) near Point Barrow, Alaska, Spring 1985

JOHN C. GEORGE,[1] CHRISTOPHER CLARK,[2] GEOFF M. CARROLL[1] and WILLIAM T. ELLISON[3]

(Received 28 January 1988; accepted in revised form 21 October 1988)

ABSTRACT. During a four-day period from 28 April to 1 May 1985, we observed bowhead whales breaking up through sea ice in order to breathe. Our observations were made from grounded sea ice approximately 10 km northeast of Point Barrow, Alaska, during the spring bowhead migration (14 April to 10 June). From acoustic and visual data, it was estimated that 665 whales passed the observation perches during this four-day period. However, only 117 (17%) whales were seen. The remaining whales either passed underneath the ice or were beyond the range of the visual observers. Whales used their heads, in the area of the blowholes, to push up against the ice (18 cm maximum thickness) and fracture it, creating a hummock of ice in which they were able to respire. Often during such breathing episodes, even at distances of only several hundred meters, the animal was not seen but its blows were clearly audible to the visual observers. Acoustic tracking of whales showed they avoided a large multi-year ice floe seaward of the observation perch. We hypothesize that bowheads use their calls to assess the thickness of ice in their migratory path. In assessing their calls, we suggest the whales can avoid areas where the ice is too thick to break through (to breathe) and/or too thick to provide clearance for them to swim beneath.

Key words: *Balaena mysticetus*, Point Barrow, bowhead whale, ice breaking, behavior, sea ice, singer, acoustic, anatomy, census

RÉSUMÉ. Au cours d'une période de quatre jours, du 28 avril au 1er mai 1985, on a observé des baleines franches qui remontaient à la surface en cassant la glace de mer pour respirer. Les observations ont été faites depuis la glace échouée, à un endroit situé à 10 km environ de Point Barrow en Alaska, durant la migration de printemps des baleines franches (du 14 avril au 10 juin). D'après les données acoustiques et visuelles, on a estimé que 665 baleines sont passées près des perchoirs d'observation au cours de ces quatre jours. Cependant, seulement 117 baleines (17%) ont été aperçues. Le reste des baleines est passé soit sous la glace, soit trop loin des observateurs pour que ceux-ci puissent les voir. Les baleines se servaient de leur tête, dans la zone de l'évent, pour repousser la glace (épaisseur maximum de 18 cm) et la fracturer, créant un hummock de glace où elles étaient capables de respirer. Souvent, au cours de ces respirations, même à des distances de seulement quelques centaines de mètres, l'animal n'était pas visible mais ses souffles étaient nettement audibles pour les observateurs visuels. La surveillance acoustique des baleines montrait qu'elles évitaient un gros floe de plusieurs années, en direction du large à partir du perchoir d'observation. On émet l'hypothèse que les baleines franches se servent de leurs cris pour évaluer l'épaisseur de la glace sur le parcours de leur migration. L'évaluation de leurs cris nous amène à suggérer que les baleines peuvent éviter des zones où la glace est trop épaisse pour qu'elles puissent la casser (pour respirer) ou pour qu'elles aient la place de nager en dessous, ou les deux à la fois.

Mots clés: *Balaena mysticetus*, Point Barrow, baleine franche, casser la glace, comportement, glace de mer, chanteuse, acoustique, anatomie, dénombrement

Traduit pour le journal par Nésida Loyer.

INTRODUCTION

The Inupiat Eskimo whale hunters of arctic Alaska have known for centuries and, more recently, researchers have observed that bowhead whales have the ability to break relatively thick sea ice in order to breathe (blow) (Scammon, 1968; Carroll and Smithhisler, 1980; Fraker, 1984; Krogman *et al.*, 1986). Carroll and Smithhisler (1980) reported an incident in the early 1960s at Little Diomede Island during which John J. Burns observed an individual whale breaking ice 23 cm thick. Accounts by Eskimo whaling crews of bowheads breaking ice <20 cm are fairly common. However, in the 1930s a crew witnessed an unusual event in which a bowhead broke through ice approximately 60 cm in thickness about 6 km southwest of Barrow (H. Brower, pers. comm. 1988).

Bowheads likely begin their northward migration in March (during the maximal extent of the polar pack ice) from wintering areas in the Bering Sea en route to the Canadian Beaufort Sea (Braham *et al.*, 1980; Braham *et al.*, 1984; Miller *et al.*, 1986). Along the migratory route, they negotiate a tenuous system of leads (linear cracks in the sea ice), which often become refrozen or blocked by heavy multi-year ice (Ljungblad, 1981). Accordingly, in order for bowheads to extend their range into the High Arctic seas, morphological, physiological and behavioral adaptations to the ice-dominated environment, such as ice breaking and under-ice navigation abilities, would be expected.

Extensive observations of bowhead whales (over 8000 h of effort since 1978) have been made during the visual census of bowhead whales off Point Barrow, Alaska. During these observations, we have observed whales utilizing very small pools of open water, often just large enough to accommodate their blowholes. Sometimes, whales were detected by seeing or hearing only their distinctive blows (Carroll and Smithhisler, 1980; Dronenburg *et al.*, 1986).

In bowhead population estimates made from 1977 to 1984, it was assumed that under conditions when there was no open water (referred to as a closed lead condition), whales did not have access to openings in the ice for breathing and therefore would not migrate through the censusing area (International Whaling Commission, 1986; Zeh *et al.*, 1986a; Zeh *et al.*, 1986b).

However, during the 1984 spring census effort off Point Barrow, Alaska, a large number of bowhead whale calls (8958) were recorded throughout a four-day period, 3 May to 7 May, when the lead was closed by an extensive field of new and

[1]Department of Wildlife Management, North Slope Borough, Box 69, Barrow, Alaska 99723, U.S.A.
[2]Laboratory of Ornithology, Cornell University, Ithaca, New York 14850, U.S.A.
[3]Marine Acoustics, 240 Oxford Drive, Cotuit, Massachusetts 02635, U.S.A.

old ice. Acoustic location and tracking analyses were applied to a 31 h sample containing 2978 calls. These analyses revealed that, during the sample period, at least 139 whales passed, yet only three whales were seen (Clark *et al.*, 1986). These results clearly indicate that many whales can pass unseen through ice-covered leads. The results also indicate that the whales were (somehow) able to navigate through heavy ice and either find small openings or force their way through the ice to breathe.

Prior to our findings, there were no estimates of the numbers of whales migrating under the sea ice during spring migration, no detailed observations on how bowheads physically break sea ice, and no data on possible under-ice navigation techniques.

In this paper we describe (1) previously unreported observations of bowhead whales breaking ice for breathing holes and migrating through ice-covered water during April 1985. We present evidence that (2) many whales passed the census site unseen by visual observers and apparently (3) avoided swimming under a large floe of thick (10-20 m) multi-year ice. We also discuss the possibility that (4) bowheads use their loud (frequency modulated) FM calls as well as (5) visual cues to navigate around obstructions and to find areas of open water or thin ice.

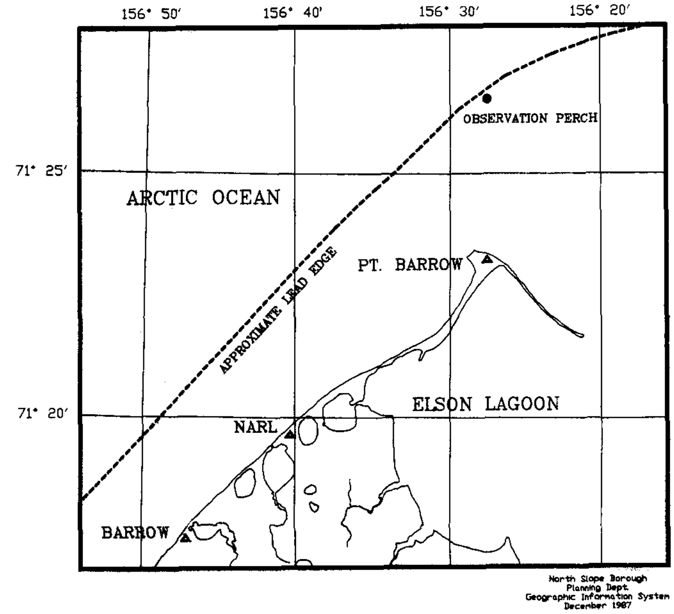

FIG. 1. The location of the observation site near Point Barrow during 27 April to 2 May 1985. The extent of the shorefast ice edge is indicated by a dashed line.

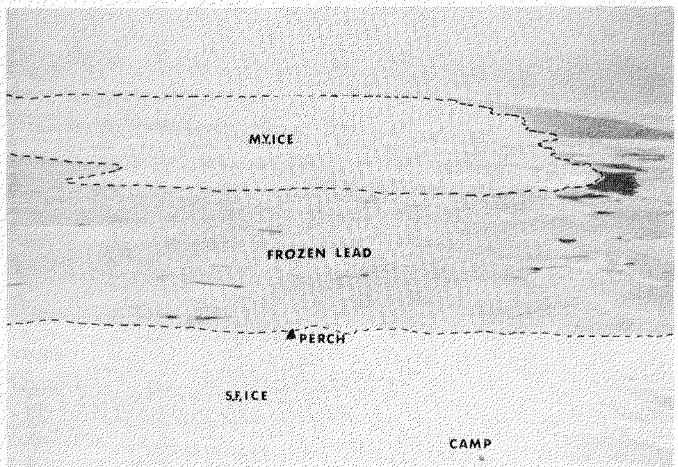

FIG. 2. Aerial photograph (looking northwest) of the sea ice in the region of the visual observation perch. A large multi-year ice floe (M.Y.ICE) was located ca. 2.5 km seaward of the shorefast ice (S.F.ICE). The region between is the refrozen lead through which the whales migrated. (Photo courtesy of David Rugh, National Marine Mammal Lab, Seattle, WA.)

METHODS

We made whale observations from a grounded pressure ridge, or "perch," on the shorefast ice about 10 km north of Point Barrow, Alaska (71°26.10′N latitude and 156°26.05′W longitude) (Fig. 1). Two visual observation sites, referred to as perches, were located 335 m apart on the edge of the shorefast ice very near the lead system where the water depth was 30 m. During these observations a large floe of multi-year pack ice approximately 10 km^2 was fixed approximately 2.0 km seaward of the perches. New, thinner ice had formed around it, essentially covering the entire lead. The floe had characteristics of old multi-year ice (LaBelle *et al.*, 1983) (Fig. 2). Such ice often has keels greater than 20 m in depth.

We made whale observations in a manner consistent with those made in past years (Krogman and Rugh, 1983). Observers used a theodolite to determine the position of whales when they were at the surface (Clark and Clark, 1980; Rugh and Cubbage, 1980; George *et al.*, 1987). For each theodolite (whale) sighting, the time, group position, number in the group, and whether it was a new or duplicate sighting was recorded.

Acoustic technicians made multiple-channel (sound) recordings from an array of three hydrophones located along the lead edge (Clark *et al.*, 1986). Each hydrophone was cabled directly to an FM sonobuoy transmitter (Sippican Ocean Systems, Marion, MA) that broadcast the signals from the hydrophone on a separate radio frequency channel. These signals were received and recorded on a four-channel tape recorder (TEAC R-61D, available from: J. Wolfe Enterprises Inc., North Hollywood, CA) operating in a mobile research hut located on stable ice, approximately 1-2 km from the sonobuoys. Acoustic observers monitored hydrophones and "field tallied" readily audible whale calls in 15-minute bins through the entire day. Later the tapes were converted into continuous two-channel spectrograms on which all (many calls were missed in the field tally) bowhead calls were identified and their times of occurrence noted. Attempts were made to locate all calling whales using a sound-location system (Clark *et al.*, 1986). After the sources of calls were located, the file of acoustic locations was processed by a program that linked the locations into whale swimming paths or tracks (Sonntag *et al.*, 1986). The southern and western margin of the multi-year ice (seaward of the perch) was determined by happenstance during a calibration experiment of the acoustic location system. In the experiment sounds were played into the water at various stations about 200-500 meters from the edge of the multi-year floe. We verified the station locations using horizontal theodolite bearings and an electronic distance meter and approximated the overall shape of the multi-year floe by using aerial photographs.

Gentleman and Zeh (1987) combined the acoustic location and visual sighting data and, using a single mark recapture release model, estimated the number of whales that passed the census point during the study period.

RESULTS

Visual observations during the 1985 census operated from 9 April to 14 June, while acoustic surveillance extended from 14 April to 10 June. The first visual sighting and the first acoustic recording of a whale occurred on 21 April. The visual count for the entire season was 1251, and 22 007 calls were field tallied. A total of 3058 calls were field tallied during the four-day study period (Table 1). A summary of the daily observations and calls field tallied for the period from 27 April to 2 May is listed in Table 1. Combining the visual and acoustic data sets, Gentleman and Zeh (1987) estimated that 665 whales passed through the observation area during the 96-hour period beginning at 0000 h on 28 April and ending at 2400 h on 1 May.

TABLE 1. Numbers of whales sighted, calls field tallied per day and estimated number of bowhead whales passing Point Barrow between 28 April and 2 May 1985

Date	Whales sighted[1]	Calls/day[2]	Estimated whales[3]
4/27	1	22	–
4/28	6	1414	
4/29	79	642	235[4]
4/30	14	702	
5/1	18	300	430[5]
5/2	1	2	–
Totals	119	3082	665

[1]Whales sighted refers to those seen for the first time.
[2]Calls/day refers to the number of bowhead calls field tallied per day.
[3]The estimated numbers of whales were derived from the integration of visual and acoustic data (Gentleman and Zeh, 1987).
[4]Estimated whale passage for the period 00:00 on 28 April to 02:39 on 29 April.
[5]Estimated whale passage for the period 0.4:57 on 29 April to 24:00 on 1 May.

Ice-Breaking Behavioral Observations

From 15 to 21 April, in the region of the perches, there was an open lead of water but only one whale was seen. The lead began refreezing on 21 April, leaving 10-15% open water. However, 43 different whales were sighted in small areas of open water between 21 and 23 April. By 26 April observers estimated there was 1% open water. The new ice covering the lead averaged 14-18 cm in thickness. Beginning on 28 April and continuing until 1 May, an estimated 665 bowhead whales migrated past the perch (Table 1; Fig. 3). Virtually all of the whales must have either broken through the ice in order to breathe or used existing holes produced by earlier passing whales. That is, the lead was refrozen over several kilometers, which required the animals to surface in the refrozen zone. In breaking the ice, the whales slowly exerted pressure with the dorsal surface of their head (in the blowhole region) until the ice fractured (Fig. 4). To exert this pressure the whales likely used fluke and flipper strokes and/or their buoyant force. In breaking through the ice, the whales formed hummocks in the ice sheet. These hummocks were raised areas of fractured ice measuring approximately 1.0×0.7 m, with a ragged central opening of several cm^2 (Fig. 5). On one occasion a whale thrust its chin (lower mandible) through the ice. The animal's body was angled sharply upward as it broke the ice, thrusting its rostrum about 1 m above the ice. The whale then submerged and placed its blowhole into the fresh opening.

In several cases the whales' exhalations blew a muddy substance out of the hummocks. The mud bespattered the ice tens of meters downwind (Fig. 5). We inspected the underside of ice near two hummocks but found no mud.

Later whales repeatedly used many of the same hummocks over the four-day period, but these quickly refroze when the

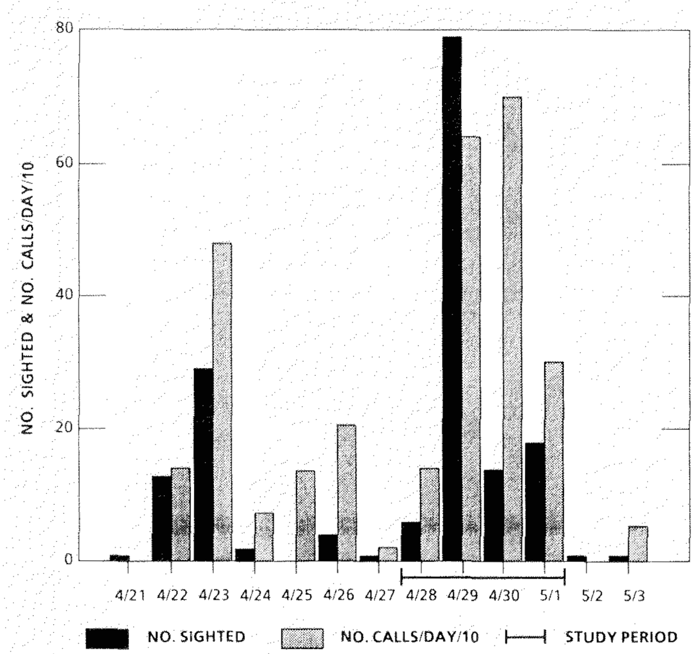

FIG. 3. Field counts of bowhead calls per day along with visual sightings per day made from the shorefast ice.

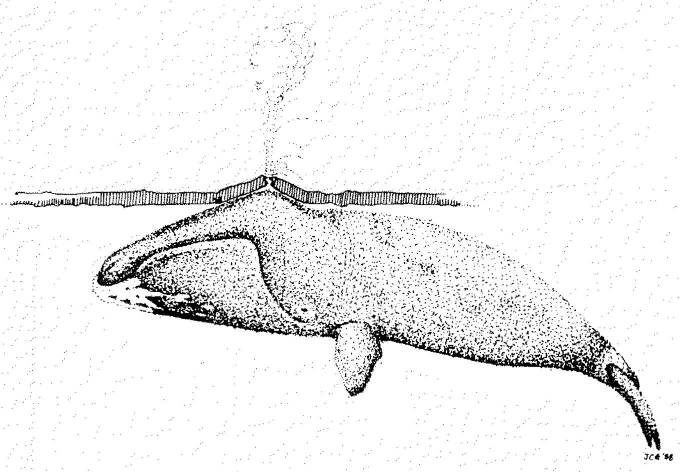

FIG. 4. Drawing of a bowhead whale using its protruding blowhole to break sea ice in order to breathe. (We could only see the whale's rostrum and approximated its body orientation for the drawing.)

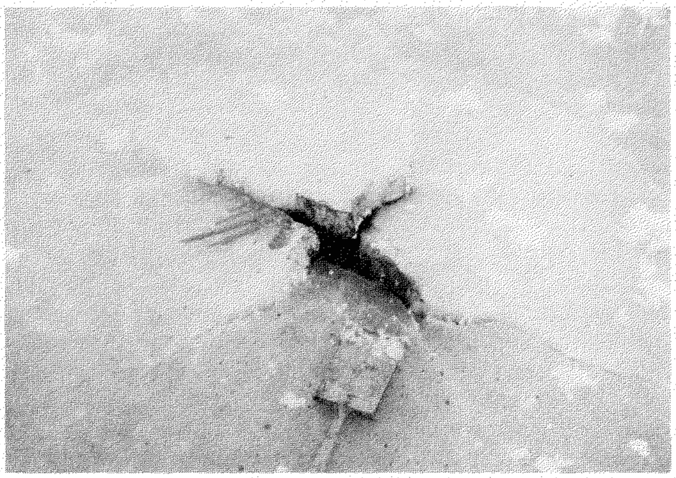

FIG. 5. A photograph of a whale hummock measuring 1.0 × 0.7 m that was pushed up through ice 14.5 cm thick. There were 50-100 such hummocks in a 1 km^2 area seaward of the observation sight. The streaks and spatters around the hummock are bottom sediments blown out of the hummock during the whale's exhalation.

passage of whales temporarily ended on 1 May (Fig. 3). There were approximately 50-100 hummocks in a 1 km^2 area directly seaward of the observation perches. A few small pools of open water (100 m^2) were available, but the whales seldom made use of them.

On many occasions during this period, blows alerted us to the presence of whales that were never seen. During the study period observers sighted 117 out of an estimated 665 whales (17%) that migrated past.

Ice Navigation-Avoidance Observations

Of the 3058 calls field tallied (28 April to 1 May), 1422 were of sufficient quality to be located. Some of the calls were from "singing" bowheads (called singers), which called nearly continuously as they passed. We plotted the 1422 call locations (Fig. 6) and locations of calls from a single "singing" bowhead (Fig. 7). Examination of the plotted locations showed an obvious absence of calls that coincided with a large multi-year ice flow (Fig. 6). Similarly, when we plotted the singer track over the approximate boundary of the floe, the whale's course indicated it deflected around the floe (Fig. 7). Hence, to explain the absence of calls in Figure 6, we surmised that the whales avoided the multi-year floe during the study period.

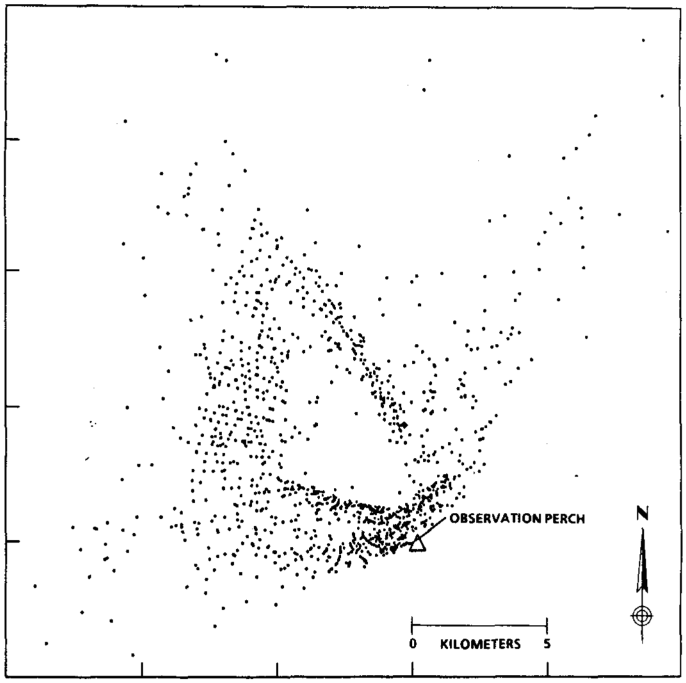

FIG. 6. Plot of the source locations of all calls from bowhead whales during the period 28 April through 1 May 1985 near Point Barrow, Alaska. The absence of calls in the center of the figure corresponds to the large multi-year ice floe. (The Y-axis is oriented to True North.)

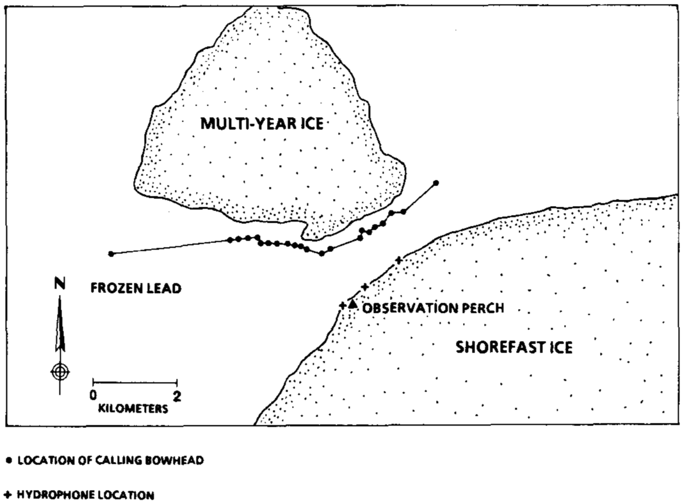

FIG. 7. Plot of "singing" bowhead track shows deflection around the multi-year ice floe that was seaward of the observation perch. The position of the multi-year ice floe was determined using aerial photographs and station positions made during a calibration test of the acoustic location system. (The Y-axis is oriented to True North.)

DISCUSSION

Ice-Breaking Behavior

Our observations confirm that bowheads can push up through ice to breathe, demonstrating one means by which whales breathe in waters entirely covered by ice. Bowheads also use existing cracks and very small holes to breathe.

The bowhead's protruding blowhole is likely an adaptation to an ice-dominated environment (Fig. 8). In support of this, the tissue between the external nares and the underlying rostral bone is composed of dense fibrous connective tissue up to 25 cm thick (Henry *et al.*, 1983). This tissue appears to be specialized for absorbing the impact experienced when breaking ice. We made close observations of feeding bowheads in late May 1985 and noted that the blowhole region in particular was roughened and abraded, possibly from ice breaking (Carroll *et al.*, 1987). We also regularly see abraded skin around the blowholes of whales landed by Eskimo hunters. Most bowheads have numerous scars on them, particularly on the dorsal areas of the head and on the flukes. Researchers and Eskimo hunters suggest that many

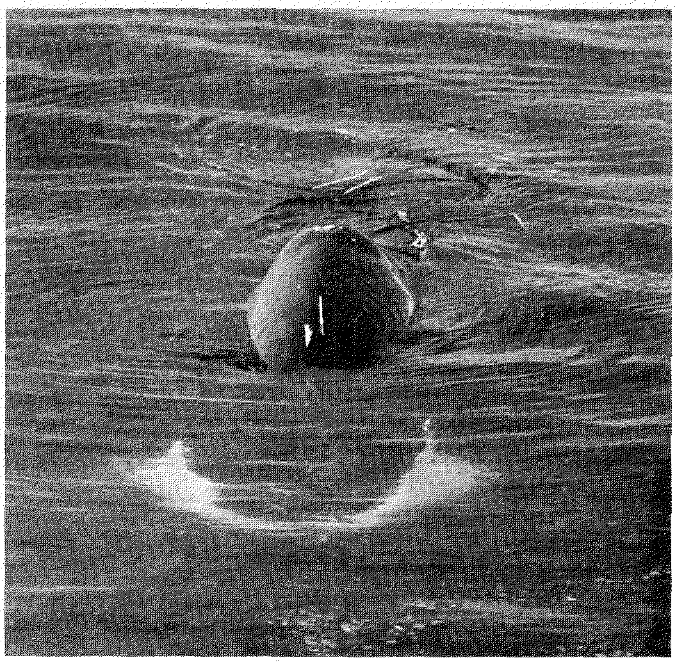

FIG. 8. A bowhead whale prior to sounding under landfast ice. Note the protruding blowhole showing several white scars. These wounds were likely ice inflicted. (Photo by Geoff Carroll.)

of these scars are ice-inflicted injuries (Albert *et al.*, 1980; Nerini *et al.*, 1984).

Other arctic and Antarctic cetaceans and some pinnipeds are known to break sea ice in order to breathe. Beluga whales (*Delphinapterus leucas*) can "maintain breathing holes and break through thin ice" (Hazard, 1988:206). However, there have been entrapments in which the belugas showed no ability to break thick (> 60 cm) ice during an entrapment near Senjavin Strait (in the Bering Sea) (Ivashin and Shevlyagin, 1987). Pacific walrus (*Odobenus rosmarus divergens*) are capable of breaking ice up to 20 cm thick (Fay, 1982). However, walrus entrapped in stable multi-year ice have become "extremely emaciated" (Fay, 1982:238). Killer whales (*Orcinus orca*) and Ringed seal (*Phoca hispida*) have also been noted to break sea ice in order to breathe (Slijper, 1979; Kelly, 1988).

The ice that the whales broke through in 1985 was 14-18 cm thick. This ice easily supported the combined weight of three men and a heavily loaded sled and snow machine (approximately 500 kg). The ice was strengthened, in part, from the relatively low air temperatures (−17° to −6°C) during the study period (Cox *et al.*, 1984).

Although there were a few small pools of open water seaward of the perch, the whales made little use of them. This failure to use these open water areas contrasts markedly with past observations in which whales sometimes used very small pools of open water and did not break through ice (Carroll and Smithhisler, 1980).

It could not be confidently determined from visual sightings whether the animals were migrating or just milling in the vicinity of the perches. Aerial and acoustic data, however, indicated that the animals were migrating. On 2 May 1985, one day after the end of the intensive acoustic activity, an aerial survey was flown by National Marine Mammal Laboratory (NMML) personnel to locate and photograph whales. Researchers flew northeast up the lead system (which was open northeast of Point Barrow) and encountered groups of migrating whales from 114 to 208 km northeast of Point Barrow (NMML field notes, 1985). These whales likely migrated past the observation perch one to two days earlier.

The acoustic evidence that the whales were migrating during the study period was more convincing than the aerial sighting. The acoustic analysis consisted of 1422 acoustic locations for the period 28 April to 1 May and from singer tracks. Sonntag *et al.* (1986) present results from applying the tracking algorithm to the acoustic locations using several migration directions. The maximum number of linkages occurred between 65 and 85° (True heading), a value almost identical to the migration angle as determined from visual sightings before and after the lead refroze (Gentleman and Zeh, 1987). Tracks of singing whales indicate that singing bowheads were, in fact, moving (migrating) in the 65-85° direction. Singer tracks do not require the tracking algorithm and therefore provide an independent and more precise means of demonstrating migration.

Under-ice migratory behavior has important implications for population estimates of bowhead whales passing Point Barrow, Alaska. That is, this behavior in part explains the wide variation in visual counts between seasons, i.e., 669 in 1984 to 1888 in 1986 (George *et al.*, 1987). The low proportion of visual sightings during the study period (17%) is primarily a result of the ice cover obscuring the whales from the observers' view, although many whales acoustically recorded were also beyond visual range. Previous to the acoustic censusing efforts, it was assumed that very few bowheads were migrating during periods of heavy ice, since few if any whales could be seen. As a result of acoustic information, however, it is now known that many whales continue to migrate even during heavy ice conditions. For instance, during a 31-hour period in May 1984 when there was nearly 100% ice cover, at least 139 different whales were located acoustically when only 3 were seen (Clark *et al.*, 1986). In past years, the highest visual counts correspond with seasons during which the lead was generally open (George *et al.*, 1987).

While there is evidence that bowheads can migrate through most ice conditions, some conditions have blocked the northward migration of bowheads. In spring of 1980, Ljungblad (1981) made aerial observations of bowheads that were apparently blocked by continuous multi-year ice in the Bering Strait region. Consequently, the typical arrival date for bowhead whales at Barrow was delayed approximately one month (Johnson *et al.*, 1981).

Nerini *et al.* (1984) summarized historic literature regarding ice entrapments and drownings of bowhead whales. Several drownings, sometimes involving 10 or more animals in some cases, were reported in the Soviet Chukchi Sea, the Bering Sea, and Disco Bay, Greenland. In 1981 we observed a small bowhead (from 3 m away) that seemed to be entrapped in a closing lead filled with slush ice. Unfortunately, we had to evacuate the sea ice and do not know the fate of the animal.

Documented entrapments represent only a few cases over 200 years. They do, however, indicate that the bowheads' ability to assess ice conditions is not infallible. These observations further suggest (indirectly) that there is strong selection for adaptations that allow the bowheads to perceive a variety of ice conditions, navigate through heavy ice, and find breathing areas during hazardous situations.

Ice Navigation-Assessment Behavior

Bowheads probably find breathing holes, small polynyas, and areas of thin ice through a combination of visual and acoustic cues. Several lines of evidence indicate that whales use ambient light for this purpose. The eye of the bowhead has a tapetum, which suggests that it is adapted to low-light conditions (Dubielzig and Aguirre, 1981). Such an adaptation would be useful for living in dark, turbid waters and, perhaps, for detecting cracks in the sea ice. Use of ambient light might explain the repeated use of the hummocks by different animals. We also observed, in a large ice pan (approximately 400 × 400 m), a single hummock precisely centered in a lone snow machine trail made hours earlier (Fig. 9). The snow machine compressed the thin snow layer onto the wet sea ice, causing the snow to melt and allowing more light to penetrate. The animal may have judged the track to be a small crack and broke through the ice beneath the track. The maximum distance at which a bowhead can detect a crack or other suitable breathing site remains unknown.

FIG. 9. A hummock from a bowhead whale that pushed up underneath a track made earlier by a snow machine. The ice was 18-20 cm thick in this area. The whale may have mistaken the track for a thin crack in the sea ice.

In addition to using ambient light, Ellison *et al.* (1987) suggest that bowhead whales may be able to assess ice conditions acoustically by using their FM calls. Their calculations show that the reflection of a bowhead call off the underwater keels of heavily ridged pack ice (10 m in thickness) is 20-30 dB greater than its reflection off new ice (0.25 m in thickness). Thus, a bowhead could determine where there is thin (flat) or thick (generally rough) ice ahead by perceiving the relative level of its own call as it is reflected off the ice. There is other circumstantial evidence that bowheads avoid thick-ridged ice based on the acoustic location data gathered during the 28 April to 1 May period. When all the whale call locations were plotted, they showed an obvious absence of acoustic locations northwest of the perch (Fig. 6). This paucity of call locations corresponds with the position of the large multi-year ice floe in front of the perch (Fig. 2). The absence of calling whales in the area of the floe implies that the whales either avoided swimming underneath it or swam underneath it but made no sounds. It would seem rather unusual for all whales to stop calling when they were underneath the floe, but we have no data on this subject. The floe may also have been grounded in places, preventing the whales from swimming underneath it. Furthermore one singer, for which there is an extensive track during this period, clearly changed its course while singing and swam around the floe (Fig. 6). The precise distance the singer was from the ice floe when it changed course could not be determined. Based on this evidence, we suspect that the whales detected the floe by perceiving the strength of their reflected calls off its deep walls and keels and swam around it. Though we can only suggest the use of reflected calls, it seems logical that such a huge animal as a bowhead whale migrating through turbid and/or dark waters would require some system to avoid collisions with deep ice keels.

A matter that is not entirely resolved is the source of sediments on the ice around the hummocks. This mud was probably on the whales' blowhole area when they respired. We have noted mud on blowholes of whales landed by Eskimo hunters. The Eskimo hunters and observations by Würsig *et al.* (1985) tell us that bowheads do, at times, swim in an inverted position. However, whales following each other through churned-up mud (via fluke strokes near the bottom) could become coated with sediments while upright. Aerial observers often see whales with mud on them in the Point Barrow area during spring migration (Carroll *et al.*, 1987).

All of the hummocks that we inspected had some amount of sediment in and around them. We cut two test holes in the surrounding ice 1-2 m from the hummocks to determine if the mud was specific to the hummocks or generally coated the underside of the ice. No mud was noted below the ice, which supports our feeling that the mud originated from the whales.

CONCLUSIONS

Our data indicate that large numbers of bowhead whales can travel underneath the ice and apparently can easily break ice less than 20 cm thick. Eskimo hunters, however, have witnessed bowheads break ice approximately 60 cm thick. This behavior, in part, explains the wide variation in visual counts at Point Barrow over the last 10 years and has significant effects on population estimates. There are, however, ice conditions that block the northward migration of bowheads. For under-ice navigation and avoidance of large multi-year floes, bowheads appear to use ambient light cues and, perhaps, the echoes of their calls off the keels of thick ice. The protruding blowhole is probably a morphological adaptation to living in ice-dominated waters and is used to break through ice in order to breathe. The substance that was blown from the ice hummocks by the whales' exhalations was likely bottom sediment that adhered to their blowhole area.

ACKNOWLEDGEMENTS

We would like to thank the crew members and supporting agencies of the bowhead census. The field crew included Perry Anashugak, Salena Brotherton, Joe Burgener, Susan Carver, Diana Dronenburg, Kurt Johnson, Ruth Johnson, Brendan Kelly, Simon Koonook, Donna McDonald, Mary Moore, Elaine Patkotak, Mike Pielorz, Lori Quakenbush, Dave Ramey, Kip Redington, Ellen Sales, Karen Schalka, Kathy Turco, Rick Yackley, and Joanne Young.

Thomas Albert, of the Department of Wildlife Management, North Slope Borough, provided editorial advice on the manuscript.

Judy Zeh, of the Department of Statistics, University of Washington, kindly reviewed and provided information for the manuscript. We are indebted to Thomas Brower, Sr., and Harry Brower, Sr., for sharing their knowledge gained from many years on the sea ice at Barrow, Alaska.

David Rugh, of the National Marine Mammal Laboratory, NMFS, Seattle, and John Richardson, of LGL, Ltd., made excellent editorial suggestions and substantive additions.

Funding was provided by the Alaska Department of Natural Resources and the North Slope Borough.

REFERENCES

ALBERT, T.F., MIGAKI, G., CASEY, H.W., and PHILO, L.M. 1980. Healed penetrating injury of a bowhead whale. Marine Fisheries Review 42(9-10):92-96.

BRAHAM, H.W., FRAKER, M.A., and KROGMAN, B.D. 1980. Spring migration of the western arctic population of bowhead whales. Marine Fisheries Review 42(9-10):36-45.

BRAHAM, H.W., KROGMAN, B.D., and CARROLL, G.M. 1984. Bowhead and white whale migration, distribution, and abundance in the Bering, Chukchi, and Beaufort Seas, 1975-78. NOAA Technical Report. NMFS SSRF-778 NOAA, Rockville, MD. 39 p.

CARROLL, G.M., and SMITHHISLER, J.R. 1980. Observations of bowhead whales during spring migration. Marine Fisheries Review 42(9-10):80-85.

CARROLL, G.M., GEORGE, J.C., LOWRY, L.F., and COYLE, K.O. 1987. Bowhead whale (*Balaena mysticetus*) feeding near Point Barrow, Alaska during the 1985 spring migration. Arctic 40(2):105-110.

CLARK, C.W., ELLISON, W.T., and BEEMAN, K. 1986. A preliminary account of the acoustic study conducted during the 1985 spring bowhead whale, *Balaena mysticetus*, migration off Point Barrow, AK. Report International Whaling Commission 36:311-317.

CLARK, J.M., and CLARK, C.W. 1980. Sound playback experiments with southern right whales, *Eubalaena australis*. Science 207:663-664.

COX, G.F.N., RICHTER-MENGE, J.A., WEEKS, W.S., MILLER, M., and BOSWORTH, H. 1984. Mechanical properties of multi-year sea ice. C.R.R.E.L. Report 84-9. 105 p.

DRONENBURG, R.B., GEORGE, J.C., KROGMAN, B.K., and SONNTAG, R.M. 1986. Report of the 1984 spring bowhead whale (*Balaena mysticetus*) ice-based census. Report International Whaling Commission 36:293-298.

DUBIELZIG, R., and AGUIRRE, G. 1981. Morphological studies of the visual apparatus of the bowhead whale, *Balaena mysticetus*. In: Albert, T.F., ed. Tissue Structural Studies and Other Investigation on the Biology of Endangered Whales in the Beaufort Sea. Report to the Bureau of Land Management from the Department of Veterinary Science, University of Maryland, College Park, MD 20742. 157-172. Unpubl. report. Available from: Minerals Management Service, 949 E. 36*th* St., Room 110, Anchorage, AK 99508-4302.

ELLISON, W.T., CLARK, C.W., and BISHOP, G.C. 1987. Potential use of surface reverberation by bowhead whales, *Balaena mysticetus*, in under-ice navigation: preliminary considerations. Report International Whaling Commission 37:329-332.

FAY, F.H. 1982. Ecology and biology of the Pacific walrus, *Odobenus rosmarus divergens Illiger.* North American Fauna 74. 279 p.

FRAKER, M. 1984. *Balaena mysticetus*: whales, oil, and whaling in the arctic. Sohio Alaska Petroleum Company and BP Alaska Exploration Inc., P.O. Box 6612, Anchorage, AK 99502-0612. 63 p.

GENTLEMAN, R., and ZEH, J. 1987. A statistical model for estimating the number of bowhead whales, *Balaena mysticetus*, passing a census point from combined visual and acoustic data. Report International Whaling Commission 37:313-328.

GEORGE, J.C., CARROLL, G.M., TARPLEY, R.J., ALBERT, T.F., and YACKLEY, R.L. 1987. Report of field activities pertaining to the spring 1986 census of bowhead whales, *Balaena mysticetus*, off Point Barrow, Alaska with observations on the subsistence hunt. Report International Whaling Commission 37:301-308.

HAZARD, K. 1988. Beluga whale, *Delphinapterus leucas*. In: Lentfer, J.W., ed. Selected marine mammals of Alaska: species accounts with research and management recommendations. Marine Mammal Commission, 1625 I Street N.W., Washington, D.C. 195-236.

HENRY, R.W., HALDIMAN, J.T., ALBERT, T.F., HENK, W.G., ABDEL-BAKI, Y.Z., and DUFFIELD, D.W. 1983. Gross anatomy of the respiratory system of the bowhead whale, *Balaena mysticetus*. The Anatomical Record 207:435-449.

INTERNATIONAL WHALING COMMISSION. 1986. Report of the subcommittee on protected species and aboriginal subsistence whaling (Annex H). Report International Whaling Commission 36:95-111.

IVASHIN, M.V., and SHEVLYAGIN, K.V. 1987. The white whale (*Delphinapterus leucas Pallas*, 1776): entrapment and escape in the ice of Senjavin Strait, USSR. Report International Whaling Commission 37:357-360.

JOHNSON, J.H., BRAHAM, H.W., KROGMAN, B.D., MARQUETTE, W.M., SONNTAG, R.M., and RUGH, D.J. 1981. Bowhead whale research: June 1979 to June 1980. Report International Whaling Commission 31:461-475.

KELLY, B.P. 1988. Ring Seal, *Phoca hispida*. In: Lentfer, J.W., ed. Selected marine mammals of Alaska: species accounts with research and management recommendations. Marine Mammal Commission, 1625 I Street N.W., Washington, D.C. 57-76.

KROGMAN, B.D., and RUGH, D. 1983. Instructions for conducting a census of bowhead whales from ice-based observation points near Point Barrow, Alaska. NOAA Technical Memorandum NMFS F/NWC-45. U.S. Department of Commerce. Available from: National Marine Mammal Laboratory, Building No. 4, 7600 Sand Point Way NE, Seattle, WA 98115.

KROGMAN, B.D., GEORGE, J.C., CARROLL, G.M., ZEH, J., and SONNTAG, R.M. 1986. Preliminary results of the 1985 spring ice-based census of the Bowhead Whale, *Balaena mysticetus*, conducted near Point Barrow, Alaska. Report International Whaling Commission 36:343-352.

LaBELLE, J.C., WISE, J.L., VOELKER, R.P., SCHULZE, R.H., and WOHL, G.M. 1983. Alaska marine ice atlas. Arctic Environmental Information and Data Center, University of Alaska, 707 A Street, Anchorage, AK 99501. 302 p.

LJUNGBLAD, D.K. 1981. Aerial surveys of endangered whales in the Beaufort Sea, Chukchi Sea and northern Bering Sea. NOSC Technical Document 449, Report from Naval Ocean Systems Center, San Diego, CA, for U.S. Bureau of Land Management, Washington, D.C. 302 p.

MILLER, R.V., RUGH, D.J., and JOHNSON, J.H. 1986. The distribution of bowhead whales, *Balaena mysticetus*, in the Chukchi sea. Marine Mammal Science 2(3):214-222.

NATIONAL MARINE MAMMAL LABORATORY. 1985. Unpubl. aerial survey field notes from Spring 1985. National Marine Mammal Laboratory, Building No. 4, 7600 Sand Point Way NE, Seattle, WA 98115.

NERINI, M.K., BRAHAM, H.W., MARQUETTE, W.M., and RUGH, D.J. 1984. Life history of the bowhead whale, *Balaena mysticetus*. (Mammalia: Cetacea). The Journal of Zoology (London) 204:443-468.

RUGH, D.J., and CUBBAGE, J.C. 1980. Migration of bowhead whales past Cape Lisburne, Alaska. Marine Fisheries Review 42(9-10):46-50.

SCAMMON, C.M. 1968. The marine mammals of the northwestern coast of North America: described and illustrated, together with an account of the American whale fishery. 2nd ed. New York: Dover. 319 p.

SLIJPER, E.J. 1979. Whales. Ithaca, N.Y.: Cornell University Press. 511 p.

SONNTAG, R.M., ELLISON, W.T., CLARK, C.W., CORBIT, D.R., and KROGMAN, B.D. 1986. A description of a tracking algorithm and its application to bowhead whale acoustic location data collected during the spring migration near Point Barrow, Alaska 1984-85. Report International Whaling Commission 36:299-310.

WÜRSIG, B., DORSEY, E.M., FRAKER, M.A., PAYNE, R.S., and RICHARDSON, W.J. 1985. Behavior of bowhead whales, *Balaena mysticetus*, summering in the Beaufort Sea: a description. Fishery Bulletin U.S. 83(3):357-377.

ZEH, J.E., KO, D., KROGMAN, B.D., and SONNTAG, R.M. 1986a. Statistical considerations in estimating the number of bowhead whales, *Balaena mysticetus*, from ice-based visual census data. Report International Whaling Commission 36:317-323.

______. 1986b. A multinomial model for estimating the size of a whale population from incomplete census data. Biometrics 42:1-14.