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Autumn movements, home ranges, and winter density of narwhals (*Monodon monoceros*) tagged in Tremblay Sound, Baffin Island

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Abstract Seven narwhals (*Monodon monoceros*) were instrumented with satellite transmitters in Tremblay Sound, northeast Canada in August 1999. The whales were tracked for 5–218 days with positions received until 17 March 2000. All whales stayed in the fjord system where they were tagged until the end of August. Three whales went northwest visiting adjacent fjords before moving south, together with the three other whales, along the east coast of Baffin Island. The narwhals arrived on the wintering ground in northern Davis Strait in late October. Speed and range of movements declined once the wintering ground was reached. Dive depths increased from summer to autumn, and reached at least 1,500 m. Late summer and winter kernel home ranges were approximately 3,400 km^2 and 12,000 km^2, respectively. The relative abundance of whales on the wintering ground was 936 narwhals. Assuming that the home range defines the winter distribution of the stock, an estimated 5,348 narwhals (corrected for perception and availability bias) were present in this area.

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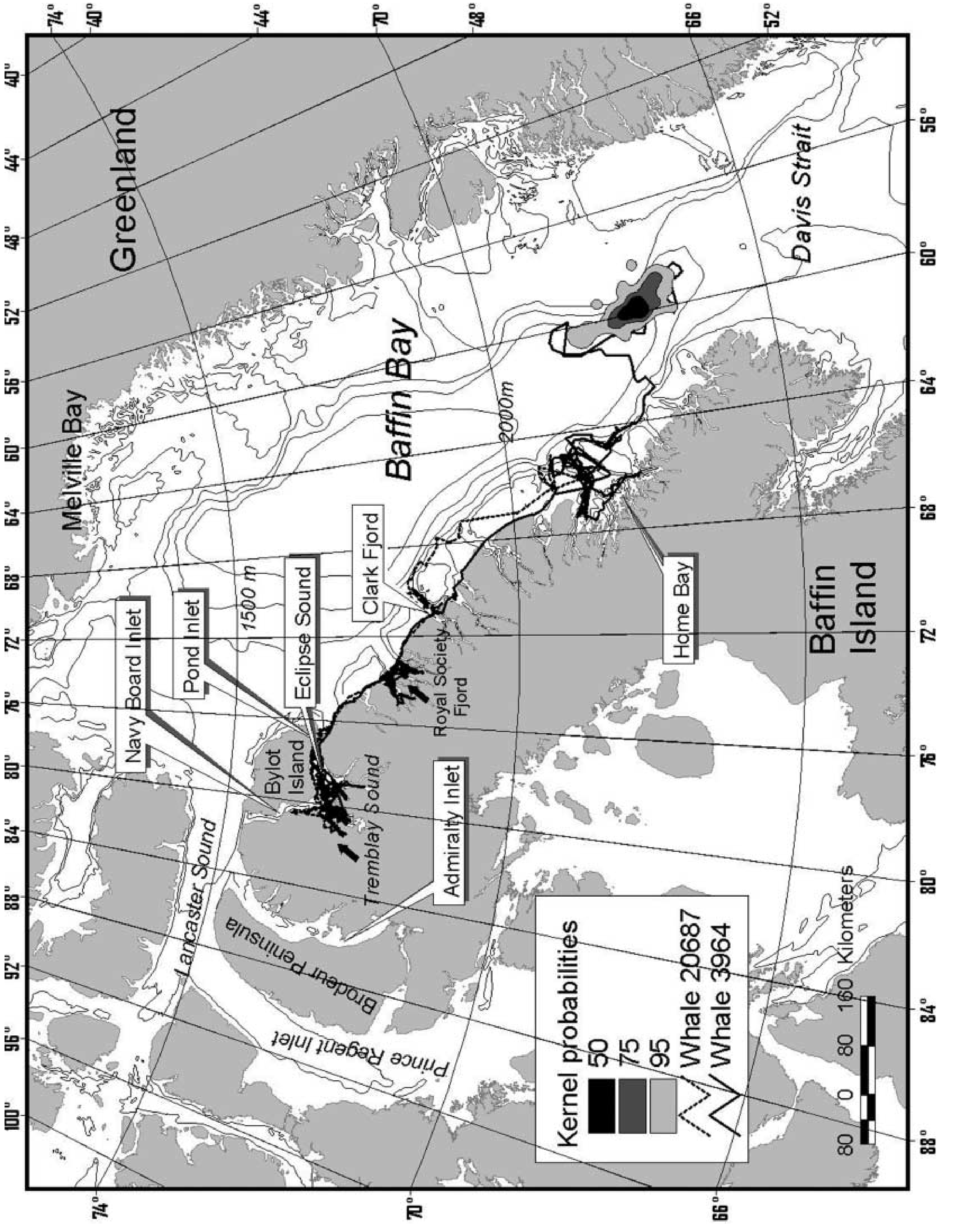
Introduction

The narwhal (*Monodon monoceros*) is a high-Arctic cetacean known for its winter preference for deep ice-covered waters. In summer, narwhals are abundant in fjord systems in the northeast Canadian archipelago and northwest Greenland (see Koski and Davis 1994; Dietz and Heide-Jørgensen 1995; Dietz et al. 2001). Earlier studies utilizing satellite telemetry to track narwhals from northwest Greenland and northeast Canada revealed that narwhals depart from their coastal summering grounds in September and follow well-defined routes in autumn towards their wintering grounds in central Baffin Bay. Narwhals seem to concentrate their time in specific areas depending on the time of year and ice cover. Wintering grounds for narwhals from both Tremblay Sound, Canada, and Melville Bay, West Greenland, appear to be in deep water on the mid- and southwestern slope in northern Davis Strait and central Baffin Bay (Dietz and Heide-Jørgensen 1995; Dietz et al. 2001). Narwhals are resident in this area from November to March in small leads and cracks in the consolidated offshore pack ice (Koski and Davis 1994).

Among the cetaceans, narwhals have one of the closest relationships with the dense pack ice (cf. Koski and Davis 1994), which makes them vulnerable to global warming-induced changes in ice conditions (Tynan and DeMaster 1997). In Baffin Bay, the duration of the sea-ice season has lengthened in the past two decades. This pattern deviates from the general pattern of a reduction in sea ice in the Arctic Ocean, and its causes are unknown (Parkinson 2000). Global warming has been predicted with considerable certainty (Wigley and Raper 2001) and will affect the ice distribution and concentration in Arctic seas. Specific effects in the Baffin Bay area are uncertain due to the simultaneous changes in the Gulf Stream and the North Atlantic Oscillation. It has been demonstrated that changes in ice distribution have a dramatic effect on the distribution of bowhead



Greenland
Melville Bay
Baffin Bay
Davis Strait
Baffin Island
Home Bay
Clark Fjord
Eclipse Sound
Pond Inlet
Navy Board Inlet
Bylot Island
Royal Society Fjord
Tremblay Sound
Admiralty Inlet
Lancaster Sound
Brodeur Peninsula
Prince Regent Inlet
1500 m
2000m
Kernel probabilities
50
75
95
Whale 20687
Whale 3964
80 0 80 160 Kilometers

Table 1. Narwhals instrumented with satellite transmitters in Tremblay Sound, NE Canada, in August 1999

Transmitter no./type	Sex	Length (cm)	Tusk length (cm)	Date of instrumentation	Date of last good-quality position	Date of last position
3964/SSC3	M	410	118	21 Aug	29 Feb 2000	18 March 2000
20168/ST-6	M	444	178	12 Aug	27 Oct 1999	30 Oct 1999
20687/ST-10	F	390	–	13 Aug	21 Oct 1999	21 Oct 1999
20688/ST-10	F	415	–	15 Aug	7 Nov 1999	7 Nov 1999
20689/ST-10	F	405	–	15 Aug	30 Oct 1999	1 Nov 1999
20690/ST-10	F	400	–	21 Aug	26 Aug 1999	27 Aug 1999
20691/ST-10	F	350	–	21 Aug	4 Oct 1999	4 Oct 1999

whales, *Balaena mysticetus*, an Arctic cetacean with an affinity for dense pack ice (Dyke et al. 1996).

Recently, exploitable resources of Greenland halibut (*Reinhardtius hippoglossoides*) have been discovered in central Baffin Bay (Treble et al. 2000), and a commercial fishery is likely to be developed. This is the same area narwhals spend the major part of the winter (Dietz and Heide-Jørgensen 1995; Dietz et al. 2001), where they are known to prey on halibut (Vibe 1950; Finley and Gibb 1982). Although the halibut fishery will occur during summer, halibut resources may be reduced the following winter when the narwhals are feeding.

This study identifies movements, diving behaviour, abundance, area usage and habitat use of narwhals captured in Tremblay Sound, Baffin Island. Data were collected from narwhals instrumented with satellite-linked radio transmitters and were used to examine whether narwhals move towards their wintering grounds in well-defined corridors by comparing departure and arrival dates from specific localities (Dietz et al. 2001). Interannual variability in movements was examined by comparison with data collected in previous years. Home range estimates were used to compare area use on the summering and wintering grounds, and maximum dives illustrated vertical utilization of habitat. Density of narwhals on the wintering ground was estimated using standard aerial line transect techniques. Assuming the size of the winter home range for the tagged whales was representative of the winter home range for the population, abundance was estimated on the wintering ground.

Materials and methods

Seven narwhals were captured at the Alpha River delta in Tremblay Sound, eastern Eclipse Sound, Canada (72°31.382′N 81°05.951′W) between 12 and 21 August 1999. They were caught using set nets deployed perpendicularly from the shore. The nets were 2-3 sections (50 m long×10 m deep) of twisted line nylon (mesh 40×40 cm). Whales were handled in the nets immediately after they were captured and belts were placed around their mid-section, tail, head and tusk for restraint. Transmitters were attached to female whales on the dorsal ridge (ST-10 Telonics transmitter unit, 0.5 W, Wildlife Computers, Redmond, Wash.) with two 8-mm polyethylene pins. Transmitters were secured to the pins with nylon washers and nuts. Transmitters were attached to the tusk of males using two stainless-steel bands (Seimac SSC3 or the Telonics ST-6 transmitter unit programmed and cast by Wildlife Computers).

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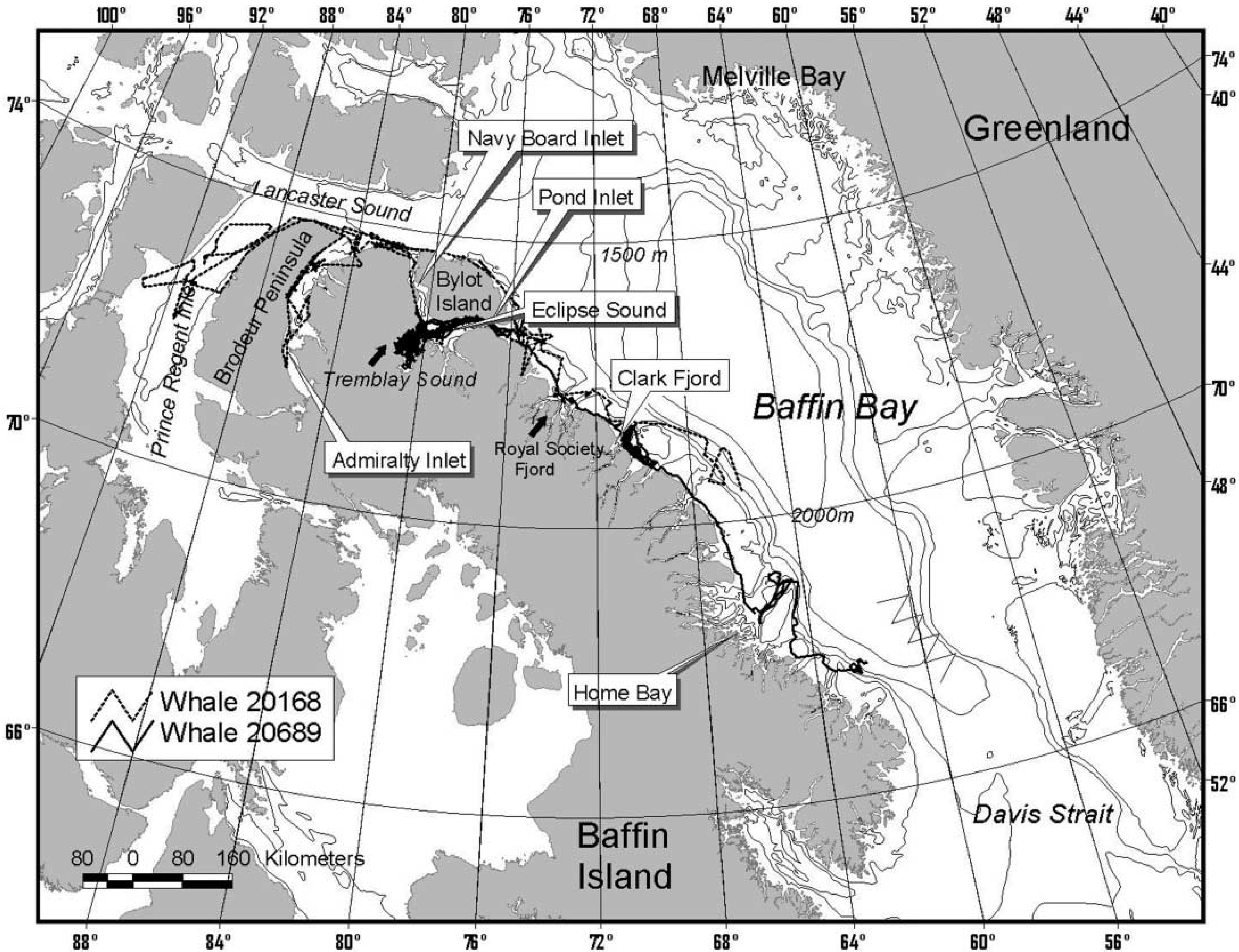
Fig. 1. Movements made by whales 20687 (*dashed line*) and 3964 (*solid line*) tagged in Tremblay Sound, Baffin Island, August 1999. Kernel home-range estimates for whale 3964 on the wintering ground are shown with shades representing probability polygons. Whale 3964 travelled 9,519 km during the entire tracking period, 3,505 km of which was between 1 November 1999 and 29 February 2000 on the wintering ground. Both whales departed east through Pond Inlet and travelled south along the coast of Baffin Island

All transmitters had a pressure transducer with a range of 0–1,000 m (resolution of 4 m) with the exception of 1 (ID 3964), which had a range of 0–1,500 m (resolution of 6 m). None of the transmitters were duty-cycled. Data from the transmitters were collected via the ARGOS system (Service Argos 1989; Harris et al. 1990). Transmissions began 250 ms after the whale broke the surface and the repetition rate was set to 45 s. One tag that provided only 5 days of data was excluded from the analysis and the movements of the other six whales are presented here.

Distance (straight-line distance between sequential positions of good quality) was calculated using only good-quality positions until 29 February 2000 (LC 1-3, error of <1 km) using ArcView GIS (Environmental Systems Research Institute, 1996). Positions were removed from the sample if resultant swim speeds between consecutive locations were >10 km/h. Positions received in March (when the tag was falling off the whale) were of poorer quality (LC 0, A and B). Inaccuracy in poor-quality positions in March was reduced by calculating an average daily position for days with more than three positions. Dates of departure and arrival at specific latitudes or longitudes along the southbound migratory route were compared with previous years (Dietz et al. 2001). The digital coastline and bathymetric data were obtained from the International Bathymetric Chart of the Arctic Ocean (IBCAO; Jakobsson et al. 2000).

Area usage on the summering and wintering grounds was estimated in two ways: (1) the 95, 75 and 50% fixed-kernel home range with least-squares cross validation, and (2) the minimum convex polygon home range using the Animal Movement extension in ArcView (Hoodge and Eichenlaub 1997). The areas where land overlapped with the home range were subtracted from the home-range estimates. Sequential animal positions may not be statistically independent; therefore, to minimize autocorrelation bias, an average daily position calculated from all locations on a given day was used to create home ranges. Because sample sizes affect the degree of accuracy of kernel estimates, sample sizes and dates were the same when home ranges were compared among or between whales. A winter home range was calculated for only one whale from this study, for the entire time spent in northern Davis Strait between 10 November and 17 March. A second winter home range was calculated for 10 November to 31 January to compare it with the home range calculated for a narwhal tagged in 1998/1999 during the same time period (Dietz et al. 2001). Home-range estimates were calculated for each individual month between November and March.

Density estimates of narwhals on the wintering ground were obtained from a standard line-transect aerial survey (see Buckland


Melville Bay
Greenland
Navy Board Inlet
Pond Inlet
Lancaster Sound
1500 m
Bylot Island
Eclipse Sound
Prince Regent Inlet
Brodeur Peninsula
Tremblay Sound
Clark Fjord
Baffin Bay
Royal Society Fjord
Admiralty Inlet
2000m
Home Bay
Whale 20168
Whale 20689
Davis Strait
Baffin Island
80 0 80 160 Kilometers
100° 96° 92° 88° 84° 80° 76° 72° 68° 64° 60° 56° 52° 48° 44° 40°
74° 70° 66°

◄
Fig. 2. Movements made by whales 20168 (*dashed line*) and 20689 (*solid line*) tagged in Tremblay Sound, Baffin Island, August 1999. Whale 20168 travelled north through Navy Board Inlet and west to both Admiralty Inlet and Prince Regent Inlet, returning along the northern coast of Bylot Island and south along Baffin Island. Whale 20689 travelled through Pond Inlet south along the coast of Baffin Island. The aerial survey tracklines are shown in Baffin Bay

et al. 1993) flown on 25 March 2000. A Twin Otter flying at a target altitude of 300 m and speed of 200 km/h flew 8 zig-zag systematic transects over the identified wintering ground in northern Davis Strait. Each transect was approximately 50 km long. Two observers, one on each side of the aircraft, recorded all sightings. The distance of the sightings from the track line was measured by taking the vertical angle (y) from the aircraft to the sighting when the sighting was abeam the aircraft, and determining the actual distance using: $d = H^*\tan(90–y)$, where H is the altitude of the aircraft in metres. The Twin Otter had flat windows and, therefore, the view of the area directly below the aircraft was obstructed. As a result, the area from 0 m to 200 m from the track line was not included in the analyses and the track line was assumed to be offset by 200 m. A uniform key with one cosine adjustment $[f(x) = 1/W + a \cos(\pi^* x/W)]$, where x is the distance, a is the parameter value to be fitted, and W is the transect width, was chosen to fit the distribution of sightings from the track line. The effective search half-width (ESW), mean pod size, sighting rate, density, abundance corrected for $g(0)$-bias (availability bias and detection bias were developed for belugas, *Delphinapterus leucas*, in a different area, Heide-Jørgensen and Acquarone, in press) and empirical variances were calculated with the software Distance 3.5 (Laake 1999).

Results

Movements and distances travelled

Between 12 and 21 August 1999, seven narwhals were instrumented with satellite-linked transmitters (Table 1). One transmitter failed (20690). The remaining six tagged narwhals stayed within Eclipse Sound and its tributaries until late August (Figs. 1, 2, 3). Whale ID 3964 made a visit to the deep Tay Sound (72°N 79°W) and two other whales (20687, 20689) made visits to Navy Board Inlet. These three whales moved east to Pond Inlet where they stayed in the deep northern part of the inlet until 13–30 September (Table 2). After this time, they started their southward movement along the east coast of Baffin Island. Of these 3 whales, 3964 made a visit to Royal Society Fjord, and the 2 others (20687 and 20689) spent time outside Clark Fjord. All three arrived on the northern side of the banks in Home Bay between 14 and 25 October, where they travelled northeast along the 200-m depth contour. Two of the whales left the bank off Home Bay on 28/29 October and moved south along the 500-m depth contour.

On 1 November 1999, whale 3964 arrived at the wintering ground in central Davis Strait on the continental slope on the southeastern part of the 1,500-m depth contour. The whale remained in this area until contact was lost on 17 March 2000 (Fig. 1). Travel rates calculated for the periods before and after 1 November (arrival on the wintering ground) were 85 km/day and 29 km/day, respectively. During winter, the whale was located in heavy (>9/10) consolidated pack ice, presumably using leads and cracks in the ice for breathing.

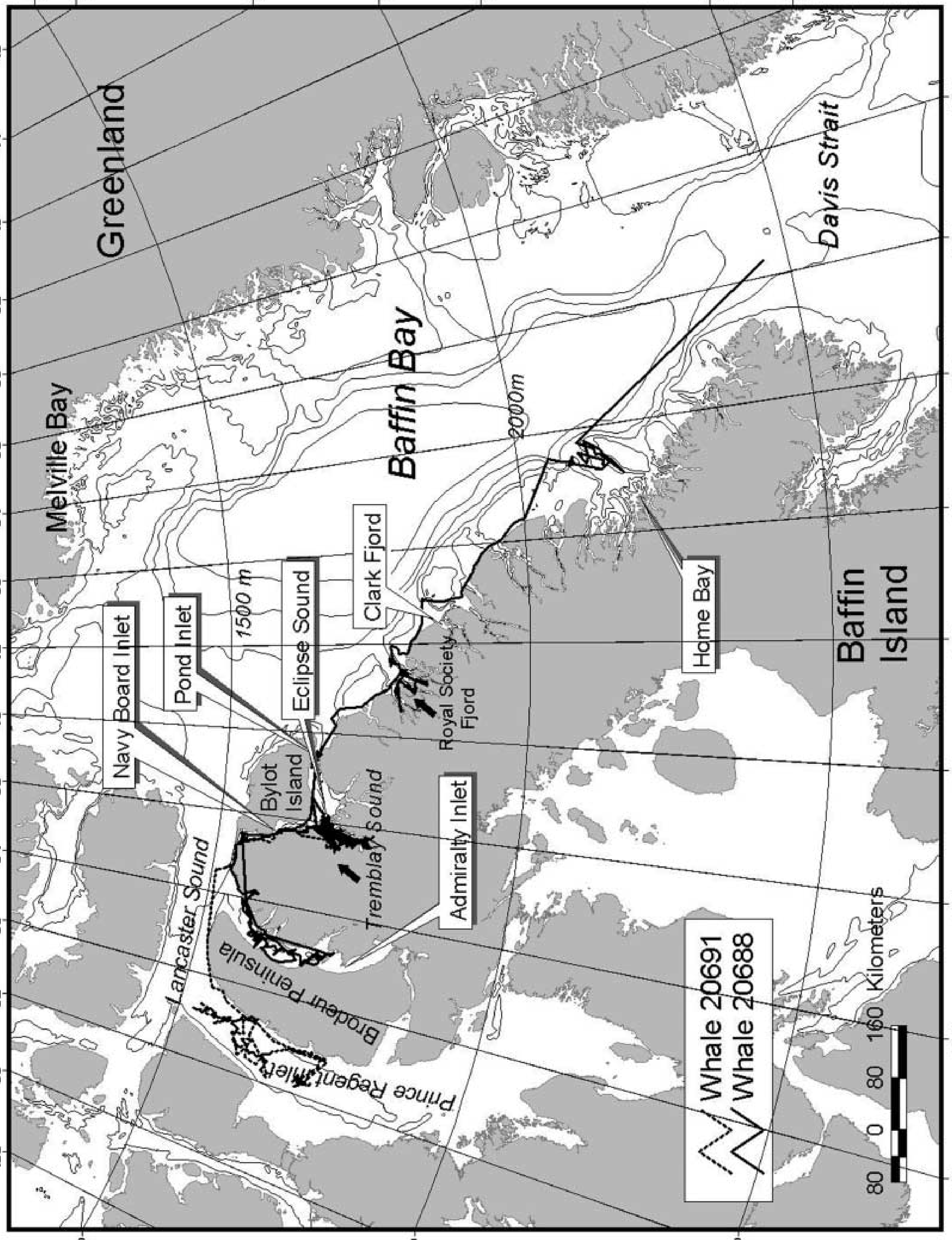
The three other whales (20168, 20688, 20691) moved north through Navy Board Inlet into Lancaster Sound (Figs. 2, 3). They left Navy Board Inlet between 26 August and 11 September and followed a route close to the coast of Baffin Island (Table 2). One of them (20691) moved west into Prince Regent Inlet, where it reached its southernmost position on 18 September (71°53′N, 90°16′W) on the east coast of the inlet. It stayed in Prince Regent Inlet until contact was lost on 4 October (Fig. 3). Another whale (20688) followed close to the coast to Admiralty Inlet where it went as far south as 72°19′N, 85°59′W on 15 September. Thereafter it returned to Navy Board Inlet on 2 October. It moved south through Navy Board Inlet and east through Pond Inlet, taking a coastal route south along Baffin Island, visiting Royal Society Fjord and the banks off Home Bay. It headed south towards Davis Strait and contact was lost on 7 November (Fig. 3). The last whale (20168) moved close along the coast towards Admiralty Inlet where it went as far south as 71°46′N, 85°56′W on 7 September. On 10 September it re-entered Lancaster Sound and moved along the northern and western coasts of Brodeur Peninsula into Prince Regent Inlet, where it reached its southernmost position in the central part of the inlet (71°51′N, 91°29′W) on 18 September. On 23 September, 20168 returned to Lancaster Sound heading east, reaching the northeastern point on Bylot Island on 5 October. From there it headed southeast, where contact was lost on 27 October (Fig. 2).

Variability in residence times in different areas

Whales either headed north in early September, or remained on the summering grounds longer into late September. Whales departed from the summering ground within ±10 days around the mean departure date (Table 2). The timing of the visits to the adjacent fjords was fairly similar for the whales that visited the same localities. During the southward migration, 5 of the whales crossed latitude 71°30′N at mean day of 6 October (range 15 Sept. to 19 Oct.), approximately 50 days after instrumentation. The whales tagged in 1999 showed greater variability in movement patterns than those tagged in Tremblay Sound in 1997 and 1998 (Dietz et al. 2001; see Discussion). Similarities included the fact that all whales exited Pond Inlet on similar dates [for 1997/1998, mean day was 22 September; for 1999, mean day was 27 September; and for all years (1997/1999) the mean day was 6 October].

Summer home range

Summer home ranges were confounded by the complex coastline in Eclipse Sound and the variability in departure dates from the summering ground. The mean 95%



Greenland
Melville Bay
Baffin Bay
Davis Strait
1500 m
2000m
Navy Board Inlet
Pond Inlet
Eclipse Sound
Clark Fjord
Home Bay
Baffin Island
Bylot Island
Royal Society Fjord
Tremblay Sound
Admiralty Inlet
Lancaster Sound
Brodeur Peninsula
Prince Regent Inlet
Whale 20691
Whale 20688
80 0 80 160 Kilometers
74°
70°
66°
40°
44°
48°
52°
56°
60°
64°
68°
72°
76°
80°
84°
88°
92°
96°
100°

◄
Fig. 3. Movements made by whales 20691 (*dashed line*) and 20688 (*solid line*) tagged in Tremblay Sound, Baffin Island, August 1999. Whale 20691 travelled north through Navy Board Inlet into Lancaster Sound and Admiralty Inlet. Whale 20688 travelled west through Navy Board Inlet into Admiralty Inlet, and then returned to Eclipse Sound and travelled south along the coast of Baffin Island

kernel home range calculated for the six whales from tagging to 31 August was 3,417 km^2 (SD 3,990, range 874–11,275 km^2) (Table 3). The high end of the range was caused by whale 20168, which left Eclipse Sound and visited neighbouring fjords earlier (26 August) than the other whales. When this whale was excluded, the average summer home range was 1,846 km^2.

The home range calculated for the summering ground is dependent on the dates used for defining residency on the summering ground. One narwhal left the Eclipse Sound area before 31 August and the home range estimate was 5 times as large as the average of the other five whales.

Winter home range

The 95% winter kernel home range for whale 3964 was 12,360 km^2 (10 November 1999 to 17 March 2000). The 95% kernel winter home range for a more restricted period (10 November 1999 to 31 January 2000, $n=83$ locations) was 10,674 km^2 (Table 4). This kernel home range compares to another whale tagged in 1998 (20162) during the same period at 13,457 km^2 ($n=83$ locations). There was 55% overlap of the kernel home range for whale 3964 with whale 20162, and 44% overlap for whale 20162 with whale 3964. This indicates that narwhals were present in the same general area in 1998/1999 and 1999/2000. However, the whale tagged in 1998 moved more widely, especially in the beginning of the period (see Dietz et al. 2001 for movements of 20162). Minimum convex polygon (MCP) home-range estimates between 10 November and 31 January for whales 3964 and 20162 were 11,046 km^2 and 12,347 km^2, respectively.

Monthly kernel home ranges estimated for whales tracked in 1998/1999 (20162) and 1999/2000 (3964) showed that whale 20162 had a November kernel home range that was 4 times larger than 3964 in the same month (Table 4). The differences between kernel home ranges for the two whales in the two other months were smaller. The MCP home ranges for the entire winter period were similar to the 95% kernel home ranges (Table 4) and MCP home-range estimates were more consistent between months.

The kernel home range calculated for 3964 for the entire winter (10 November 1999 to 17 March 2000) was not much larger than the home range calculated for the period 10 November to 31 January (12,360 km^2 vs 10,674 km^2, respectively). Monthly kernel home-range calculations for 1999 indicate that movements were

Table 2. Dates of departure from summering grounds (*NBI* Navy Board Inlet, *AI* Admiralty Inlet, *PRI* Prince Regent Inlet). Data from 1997 and 1998 from Dietz et al. (2001). Travel distances were calculated as the straight-line distance between sequential positions of good quality for all months except March. Standard deviation (*SD*) is +/− number of days

Whale ID	1997	1998			1999						Mean (SD)
	6335	20162	3961	20696	20691	20689	20168	3964	20688	20687	
Travel distance (km)	4062	7017	4516	2742	2338	5856	4878	9568	5232	3263	
No. days with good-quality positions	76	165	78	49	44	76	76	192	84	69	
Speed (km/day)	53	43	58	56	53	77	64	50	62	47	
Exit NBI (73°30′N)					11 Sept		26 Aug		11 Sept		6 Sept (9.24)
Enter AI (73.30°N)							27 Aug		12 Sept		4 Sept (11.3)
Southernmost point in AI							7 Sept		15 Sept		11 Sept (5.6)
Exit AI (73°30′N)							10 Sept		29 Sept		20 Sept (13.4)
Enter PRI (88°W)					14 Sept		11 Sept				13 Sept (2.12)
Southernmost point in PRI					18 Sept		18 Sept				18 Sept
Exit PRI (88°W)							23 Sept				23 Sept
Exit Pond Inlet (76°W)	21 Sept	20 Sept	20 Sept	28 Sept		29 Sept		13 Sept	10 Oct	30 Sept	25 Sept (8.3)
Southbound route – pass 71°30′N	28 Sept	27 Oct	22 Sept	5 Oct		8 Oct	19 Oct	15 Sept	13 Oct	3 Oct	6 Oct (13.1)
Pass 62°W	29 Oct	7 Nov						31 Oct			2 Nov (4.7)
Pass 61°W		10 Nov						1 Nov			6 Nov (6.4)

Table 3. Estimates of late summer home range for six narwhals tagged in Tremblay Sound, Baffin Island, 1999. Data are presented for the 95% fixed-kernel least-square cross validation home range (in km^2). Home ranges were calculated from average daily positions using all location qualities from the tagging date to 31 August. Means for all whales are reported, with SD in parentheses

Whale ID	95% Kernel
3964	3775
20691	874
20689	933
20688	1,695
20687	1,952
20168	11,275
Mean of all whales	3,417 (3,990)
Mean of whales (without 20168)	1,846 (1,176)

variable among months. January and March appeared to be months of increased movement on the wintering grounds, whereas the February kernel home range was smallest. The home range calculated for whale 20162 was the largest. The home ranges from the MCPs on the wintering ground are more consistent for both whales than the kernel home ranges. The home ranges for the period 10 November to 31 January are, however, fairly similar for the two methods, indicating the home range for that period was approximately 12,000 km^2.

Maximum diving depths in different areas

The mean maximum dive depth for the six whales in Eclipse Sound was 604 m (SE = 18 m) (Table 5). The three whales that moved to the west in September and visited adjacent fjords had daily maximum dives of 583 m (SE = 38 m) in Admiralty Inlet and 369 m (SE = 19 m) in Prince Regent Inlet. The four whales that exited Pond Inlet in late September increased their maximum dives to a daily average of 623 m (SE = 39 m) when travelling along the east coast of Baffin Island. All five whales increased their maximum diving depth to 727 m (SE = 17 m) after passing south of 71°30′N. Whale 3964 made mean daily dives of 1,442 m after reaching the wintering ground east of 61°W. Maximum dive depths were truncated at 1,500 m for this individual because dive depths were limited by the maximum depth readings of the depth transducer (Fig. 4). Therefore, it is likely that this whale was diving to depths greater than 1,500 m on its wintering ground.

Table 5. Mean and standard error of maximum depth of dives measured over 24 h

Area	Whale ID	Mean	SE
Eclipse Sound	3964	651	38
	20168	578	66
	20687	659	35
	20688	576	40
	20689	633	38
	20691	411	39
Admiralty Inlet	20168	484	62
	20688	659	40
Lancaster Sound	20691	408	144
Prince Regent Inlet	20168	386	28
	20691	360	25
Eastern Baffin Island	3964	744	108
	20687	651	30
	20688	707	65
	20689	558	61
South of 71°5N	3964	730	25
	20168	954	34
	20687	758	35
	20688	713	47
	20689	656	36
Wintering ground east of 61°W	3964	1443	8

Abundance of whales on the wintering ground

Areas with 10/10 sea ice were encountered on all survey transects, and narwhals were sighted only in leads and cracks intersecting the flight path. There were 21 sightings of narwhal pods during the survey. Angles were obtained for 17 of the sightings and the average distance of the 17 sightings was used to estimate the additional 4 sightings without angles. The Effective Search half-Width (ESW) was calculated as 480 m (cv = 0.17). The sighting rate was 0.052 sightings/km (cv = 0.16), the mean group size 1.4 (cv = 0.12), and the density was 0.078

Table 4. Estimates of monthly and winter home ranges (km^2) for two whales. Data are presented for the 95%, 75%, and 50% fixed-kernel least-square cross validation home range and minimum convex polygon (*MCP*) home range. Home ranges were calculated from average daily positions calculated from all location qualities. Only poor-quality positions were available between 1 and 17 March. Data from 1998 are from Dietz et al. (2001)

Period	20162 (1998–1999)				3964 (1999–2000)			
	95%	75%	50%	MCP	795%	775%	750%	MCP
November, $n = 20$	24,289	13,350	6,130	4,803	5,960	2,668	672	3,038
December, $n = 31$	6,169	2,192	565	5,001	10,138	4,180	1,778	3,167
January, $n = 30$	14,111	6,109	2,825	5,309	11,543	3,550	1,500	7,248
February, $n = 29$					6,553	3,112	1,127	3,262
March, $n = 17$					13,564	8,579	4,166	4,763
10 November–31 January, $n = 83$	13,457	6,213	2,045	12,347	10,674	3,874	1,298	11,046

whales/km^2 (cv = 0.27). Using the winter kernel home-range area estimates (≈12,000 km^2), 936 narwhals were present at the surface (cv = 0.27). The distribution of sightings had a clear shoulder at the offset of the trackline and corrections for diving whales and whales missed by the observers can thus be derived by estimating these factors on the trackline [$g(0)$, cf. Laake 1999]. When the survey was corrected for a $g(0)$ estimate of 0.175 (cv = 0.34, see Heide-Jørgensen and Acquarone, in press, and Discussion), approximately 5,348 (cv = 0.43) narwhals were present in the area, including whales that were submerged or overlooked by the observers.

Discussion

Movements and distances

The results from this study reveal higher variability in summer narwhal movement patterns than that reported in previous studies (Dietz et al. 2001). Tay Sound, a fjord > 600 m deep, was reported to be an important summering area for narwhals by Miller (1955). This area was not used by any of the ten narwhals tagged in 1997 and 1998 (Dietz et al. 2001) nor were any whales observed there during aerial surveys conducted in August 1984 (Richard et al. 1994; Dietz et al. 2001). However, in this study one whale (3964) visited Tay Sound. Additionally, studies in 1997 and 1998 did not show movements towards or within Navy Board Inlet. However, Inuit hunters report that Navy Board Inlet is a part of the summer distribution of narwhals during August (Remnant and Thomas 1992). Three of the tagged whales in this study moved north through this inlet in August, confirming the use of Navy Board Inlet by narwhals during summer.

Dietz et al. (2001) showed that narwhals tagged in Tremblay Sound moved east to Pond Inlet in September, and then moved south towards their wintering grounds between 22 and 29 September. These observations are corroborated by aerial surveys conducted during August and the first half of September in 1975, 1976 and 1981, which did not find narwhals in Lancaster Sound (Johnson et al. 1976; Renewable Resources Consulting Services 1976; Davis et al. 1978; Smith et al. 1985; Strong 1988). Based on the results from these aerial surveys and the tagging studies in 1997 and 1998, there appeared to be no large-scale exchange between summering stocks of narwhals during August and the first half of September. Our study indicates a more complex movement pattern. For example, three of our whales moved north through Navy Board Inlet into Lancaster Sound between 26 August and 11 September, visiting areas occupied by other summering stocks (Admiralty Inlet and Prince Regent Inlet) in early September (NAMMCO 2001). It is unknown if these movements represent a true mixing of summering stocks. The whales remained in these areas for brief periods and their movements occurred when all summering stocks of narwhals were beginning to make large-scale movements towards their wintering grounds. Reeves and colleagues saw many narwhals while flying along the east and west coasts of Admiralty Inlet on 4 September 1984 (R. Reeves, personal communication). The whales on the west side were heading north and those on the east side were heading south. This might indicate that even in small areas like Admiralty Inlet, there may be segregation of narwhals from different summering stocks.

The whales that were tracked through October showed a remarkable affinity for the northern part of the bank off Home Bay; they travelled along the northeast 200-m depth contour and avoided shallower depths. A very similar pattern was observed for three narwhals tracked in 1997 and 1998 (Dietz et al. 2001).

Home ranges

The fixed-kernel home-range calculations provide a probabilistic model of home range that describes the relative amount of time that an animal spends in any place. The fixed-kernel method with least-squares cross validation was used in this study, and it provides the most accurate estimates of home ranges (Erran Seaman and Powell 1996). Because of sample-size biases in calculating home ranges, data were sub-sampled to ensure a uniform sample size, representing the same days for each whale. Eighty-three observations were utilized per whale for winter kernel calculations. The March and November kernel estimates may be positively biased due to incomplete sampling periods. Smaller sample sizes are poor at identifying fine structure and overestimate home-range size for kernel distributions, contrary to other home-range estimates where small sample sizes underestimate home range (Erran Seaman and Powell 1996). It is important to note that whale 3964 (tracked during the winter 1999/2000) went to the same wintering ground in northern Davis Strait as the narwhals tagged in 1997 and 1998 (Dietz et al. 2001). There was a considerable overlap in wintering home range (about 50%) for the whales tagged in 1998 and 1999. This same area is also used as a wintering ground by narwhals from Melville Bay, West Greenland (Dietz and Heide-Jørgensen 1995).

Diving habits

The information on maximum depth of dives contributes to the understanding of habitat use. The narwhals apparently dive to the bottom or close to the bottom in the areas they inhabit in both summer and winter. Narwhals appear to utilize the full water column throughout the winter along the steep continental slope on the east side of Baffin Bay. The daily maximum dive depth to at least 1,500 m is the deepest dive recorded for a narwhal (Heide-Jørgensen and Dietz 1995). This is

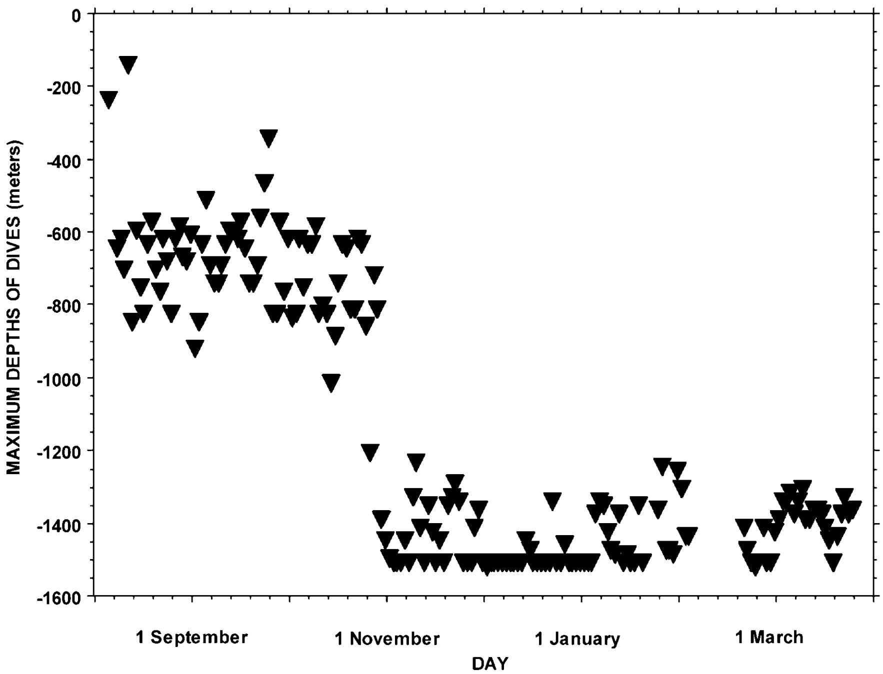


Fig. 4. Maximum dive depths (measured over 24 h) for whale 3964 from late August 1999 to mid-March 2000

slightly deeper than the deepest dives recorded for bottlenose whales (*Hyperoodon ampullatus*) using Time Depth Recorders (Hooker and Baird 1999), or sperm whales (*Physeter macrocephalus*) (Watkins et al. 1993).

Abundance on wintering ground

Narwhals from summering grounds in Eclipse Sound were estimated to number approximately 543 (95% CI: 166–1,784) whales in 1984, uncorrected for availability bias (Richard et al. 1994). This is slightly smaller than (but not significantly different) from the uncorrected estimate of 936 (95% CI: 551–1,590) whales on the wintering ground in March 2000 in this study. Narwhals from Melville Bay, West Greenland, also winter in northern Davis Strait (Dietz and Heide-Jørgensen 1995); however, no abundance estimates exist for any summering grounds in West Greenland.

The calculation of abundance on the wintering ground is based on a small sample size from a restricted area. Furthermore, the correction factor [$g(0)$] for availability and perception bias was primarily developed for belugas in West Greenland in March in 1998/1999 (Heide-Jørgensen and Acquarone, in press). The correction factor includes an estimate of 35% of the whales being visible at the surface (<6 m) and an estimate of 50% not being detected by the observers. The small sample size of the survey and the use of a correction factor for belugas in West Greenland are less than ideal and the numbers of both density and total abundance of narwhals on the wintering ground should be taken only as approximate values. Nevertheless, the aerial survey confirms the presence of large numbers of narwhals on the wintering ground.

Baffin Bay and northern Davis Strait have a fairly consistent annual build-up of consolidated pack ice, which reaches its maximum in March (Parkinson 1999). The ice coverage in March is generally classified as 9/10 pack ice or greater (Anonymous 1998), and in February 2000 the area was classified as $>9/10$ 1st-year ice (>120 cm) with floe sizes larger than 10 km (Canadian Ice Service 2000). This is the habitat where narwhals spend 4–6 months of the year, and is among the most severe ice conditions experienced by cetaceans for prolonged periods. The two other Arctic cetaceans, the beluga and the bowhead whale, also spend periods of time in dense sea ice. However, in winter they retreat to areas with loose pack ice or where predictable leads or cracks form. In Baffin Bay, belugas and bowhead whales prefer to winter either in the open pack ice off West Greenland or in the North Water polynya (Richard et al. 1998; Heide-Jørgensen and Acquarone, in press; Heide-Jørgensen et al., in press). Belugas in the Beaufort Sea have been observed moving far north into dense pack ice in autumn (Richard et al. 2001; Suydam et al. 2001). However, the belugas apparently leave the dense pack ice in the autumn, and winter in the loose pack ice in the Bering Strait.

The clear association between narwhals and the consolidated pack ice in Baffin Bay makes them vulnerable to changes in ice regimes. The sea-ice season has lengthened in the past two decades in Baffin Bay (Parkinson 1999). Global warming will likely affect ice formation in the Arctic seas; however, the specific effects on Baffin Bay remain unclear due to the simultaneous changes occurring in the Gulf Stream, the North Atlantic Oscillation and the south-going current in western Baffin Bay. Due to the restricted habitat preferences of narwhals (i.e. dependence on small leads and cracks in the dense pack ice), it is uncertain how they will adapt to changes in pack ice in Baffin Bay.

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