

CETACEAN OCCURRENCE PATTERNS IN THE AMUNDSEN AND SOUTHERN BELLINGSHAUSEN SEA SECTOR, SOUTHERN OCEAN

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ABSTRACT

We conducted 239.5 h and 3,494 km of cetacean surveys in the Amundsen and Bellingshausen seas, from 15 February to 31 March 1994; most of the area, the large portion of which was ice covered, had never before nor has it since been surveyed for cetaceans, even to the date when this paper was prepared (2006). Logistic regression and an information-theoretic approach related the occurrence of Antarctic minke whales *Balaenoptera bonaerensis* (the most abundant species) to whether we were in open- or pack-ice-covered pelagic or neritic waters, in or out of the marginal ice zone (MIZ), and north or south of the Antarctic Circumpolar Current southern boundary. Other variables included date and distance to the MIZ and shelfbreak front. Statistical analysis showed that the probability of sighting a minke, as well as killer whale—but not the case for an index to whale density—was related to the proximity of coastal polynyas in early autumn, switching offshore to the MIZ once waters within the pack began to freeze persistently later in the season. Probability of detection was higher with distance into the MIZ. Supporting these findings, the density index was strongly related to ice concentration in an inverse relationship. The strong relationship to polynyas and the MIZ indicate that sea-ice divergence altered by decadal or longer-term climate change, as described in the recent literature, could well affect any apparent, long-term trends evident in this species' abundance

if surveyed only in open or near-to-ice waters. We speculate on how the minke whale's pagophilic nature (1) could have been encouraged by large-scale industrial whaling and by competition with species more characteristic of open waters and the outer MIZ, and (2) may have protected the population somewhat during industrial whaling resulting in the much greater abundance of this species now compared to other targeted species.

Key words: Amundsen Sea, Bellingshausen Sea, cetacean abundance, cetacean ecology, marginal ice zone, killer whale, *Orcinus orca*, minke whale, *Balaenoptera bonaerensis*, polynya, sea ice, Southern Ocean.

Most Antarctic cetacean surveys, except for the few that used icebreakers (*e.g.*, Ribic *et al.* 1991, Aguayo-Lobo 1994, Thiele and Gill 1999), have been conducted in open waters or the outer marginal ice zone (*e.g.*, Kasamatsu *et al.* 1996, 1998; Thiele *et al.* 2000, 2004; Murase *et al.* 2002; Friedlaender *et al.*, 2006). As a result, the current perception in the research community is that species such as the Antarctic minke whale (*Balaenoptera bonaerensis*) or certain types of killer whale (*Orcinus orca*) are creatures mainly of near-to-ice and marginal-ice-zone (MIZ) waters (see also Brown and Lockyer 1984, Costa and Crocker 1996). This perception may be biased by survey effort that favors open waters. After all, the Antarctic minke whale is perfectly suited to exploit pack-ice habitat, having a small, slim, compact body and small appendages that allow it to fit into narrow leads between ice floes without catching on ice and a hard, sharp rostrum for breaking through newly formed sea ice in order to breathe (Thiele *et al.* 2000, Ainley *et al.* 2003). The form of the killer whale found at highest latitude, "type C," is also small bodied to exploit narrow passages in the ice (Pitman and Ensor 2003).

The aim of the major Southern Ocean cetacean surveys, that is, the IDCR/SOWER circumpolar effort, has been to track trends in the size of the minke whale population, a task that can be fulfilled only by the sort of repetitive sampling thus far employed (*e.g.*, Branch and Butterworth 2001). Unfortunately, these surveys are conducted from vessels that are not ice capable and the Antarctic marine climate has not remained constant. Over the period of these cruises (since the 1970s), portions of the Southern Ocean have seen significant fluctuations in sea-ice concentration and extent, longer or shorter sea-ice seasons, and changes in the prevalence of coastal polynyas (or post-polynyas [Arrigo and van Dijken 2003]: open waters remaining from winter-time polynyas; *e.g.*, Jacobs and Comiso 1989, 1993, 1997; Stammerjohn and Smith 1997; Jacobs and Giulivi 1998; Parkinson 2002; Zwally *et al.* 2002). Realizing this changing environment, recent authors in the proceedings of the International Whaling Commission (IWC) have questioned both the degree to which minke whales occur in pack-ice areas and, if they are prevalent therein, the potential effects of such occurrence on trend analyses (*e.g.*, Shimada *et al.* 2001, Shimada and Murase 2003, Murase and Shimada 2004). Attempts have been made to grapple with the problem and to better understand the importance of a changing sea-ice regime on minke whale distribution and assessment (Branch and Butterworth 2001, Tynan 2002, IWC, 2005, Thiele *et al.* 2005), as this is not a trivial matter, especially given the size of long-term, open-water data sets and the huge expense in time and money required to develop valid correction factors to account for whales in an ever-changing pack-ice habitat. Moreover, the standard line-transect surveys typically used in cetacean stock assessments, where constant effort must be maintained, are problematic in the pack ice.

There, even icebreakers must constantly and dramatically change course and speed in order to maintain headway; otherwise, line transect data in the pack ice can be collected only by using very expensive aircraft that can fly straight lines but with reduced sighting probability due to their rapid speed relative to the whales' diving behavior.

As a contribution to better understand the cetacean community within the Southern Ocean pack ice, herein we report results of an icebreaker-based survey conducted in the pack ice and adjacent waters of the Amundsen and southern Bellingshausen seas during autumn 1994. Owing to the heavy, persistent pack ice in this area, much of what we surveyed (and report) had never before and has not since been visited by cetacean observers, even as of the date when the analysis presented here was completed (2006). Our purpose, therefore, is to describe the factors that affected the occurrence patterns of cetaceans and especially of minke whales, which were by far the most abundant whale species encountered. We also make comparisons to the results of other surveys both in the deep and peripheral ice pack. As was the case for seabirds (reported previously: Ainley *et al.* 1998), we hypothesized that cetaceans were more likely to be seen in polynyas and that this relationship might change over time as cetaceans moved north into the MIZ, away from coastal polynyas as the season progressed. Such a hypothesis was consistent with the main purpose of our cruise: to determine why the pack ice of the study area had become more divergent in recent years.

METHODS

Surveys

Observations were made on the research icebreaker *Nathaniel B. Palmer*, cruise 94-02. On this cruise we completed a series of meridional sections extending between the coast and points well beyond the shelf break beginning at King Edward VII Peninsula, Marie Byrd Land, *ca.* 150°W, on 15 February 1994, passing east along the coast of Ellsworth Land, and ending at Marguerite Bay, Antarctic Peninsula, *ca.* 70°W, on 31 March (Fig. 1). Thus, the first section, a short one owing to the narrow shelf there, was actually at the eastern boundary of the Ross Sea. The majority of effort was in the Amundsen and Bellingshausen seas and waters to the north. Eleven sections crossed the shelf break and large-scale pack-ice edge with eight of these also crossing the southern boundary of the Antarctic Circumpolar Current (ACC). Five sections passed through coastal polynyas/postpolynyas. Conductivity-temperature-depth (CTD) casts were made at intervals along these sections in order to investigate ocean structure and specifically to detect the intrusion of warm Circumpolar Deep Water onto the continental shelf. Thus, most sections passed over depressions that projected across the shelf break toward the inner shelf. CTD data for our purposes were used to identify the Antarctic Slope Front and the southern boundary of the ACC. Because much of the cruise occurred in uncharted waters, depth was monitored continuously along most of the track using a precision depth recorder.

Cetaceans, seals, and seabirds (see Ainley *et al.* 1998) were counted using the methodology described in Ribic *et al.* (1991), as follows. Two observers worked together at 12 m above the sea surface. They simultaneously scanned, using 8× binoculars and the naked eye, a 90° area 800 m forward and to the side from the bridge wing whenever the ship was underway during daylight. We observed on the side

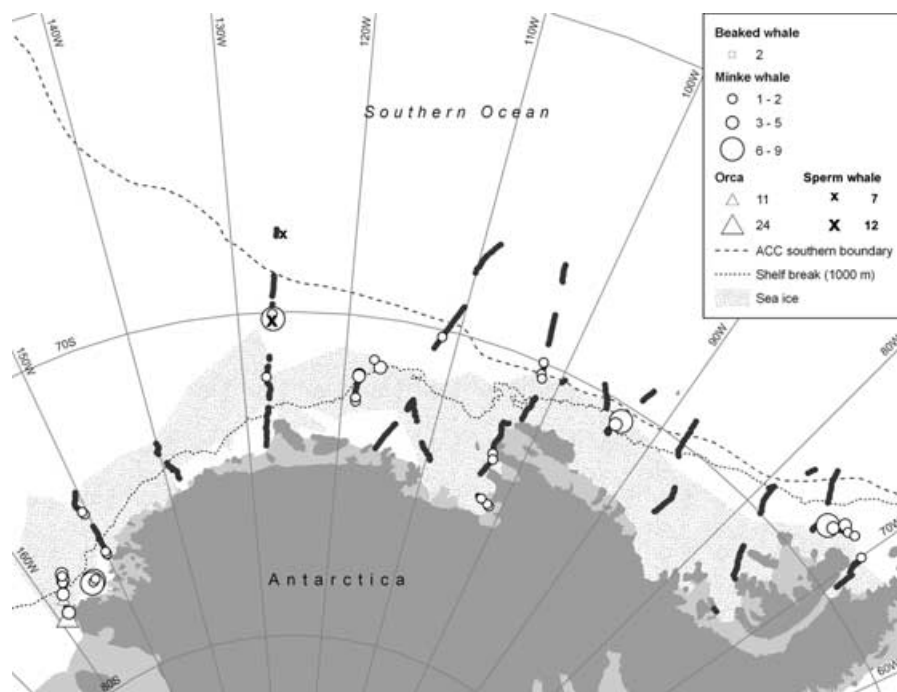


Figure 1. Cruise track in the Amundsen and Bellingshausen seas, 15 February to 31 March 1994, showing only segments on which cetacean surveys were made. Light levels were too low for adequate viewing on other segments.

having the least glare, or having open water if the ship was closely circumnavigating an extensive floe on its other side. Strip width was constant and was maintained using the range finder described by Heineman (1981). We were not on effort when we could not see well to a distance of at least 800 m owing to fog or reduced light level. Counts were continuous but partitioned into 30-min intervals as long as we were at maximum speed (21 km/h). Such a speed resulted in segments of about 11-km long. If speed changed suddenly (25%) we terminated a segment and started a new one. If, for instance, speed dropped to 11 km/h, we doubled the duration of the segment in order to maintain segment linear length. We ceased counts when speed dropped to <5 km/h, which happened in very heavy ice where there were few leads. We did not attempt to gather line-transect data because the ship was mainly in the pack ice following leads among the larger floes and, therefore, moving along a twisting course with variable speed. The whales occurred in the same or nearby leads, and angle and distance measures would have been of little use. At 800 m, we could identify all whales seen, except for some beaked whales visible only very briefly; at that distance, if acting normally, whales were not totally obscured by the height (free-board) of the sea ice in open water distant from the ship.

At the start of each segment, which coincided with the end of the previous one, we logged time and date (GMT), position, depth, ship course and speed, wind direction and speed, and ice conditions (percent cover, thickness, type—sea or glacial—new,

multiyear, aging, floe size, *etc.*; see Ainley *et al.* 1993, 1998 for more details). Ice was characterized out to 300 m and to 1 km (with assistance of observers in the ship's ice tower). Of 517 segments surveyed, wind compromised our ability to detect cetaceans within 800 m only on 14 segments, when in open seas wind speed exceeded 44 km/h. However, whales were sighted on two of these fourteen segments, so for sample size purposes we retained them all in the analysis. At other times when wind exceeded that level we were in the pack ice or within polynyas where there was very little fetch and, thus, wind-generated waves were inconsequential and the Beaufort Scale did not apply. Ocean swells were minimal in the ice as well, and the winds were never strong enough to change the surface of coastal polynyas into a froth of sea spray. Therefore, rarely did we experience sea conditions that would have differentially affected sightability of cetaceans among our census segments. The generally sub-zero temperatures increased the visibility of whale blows.

Description of Variables

The dependent variables of interest were the presence or absence of cetaceans and cetacean density (whales/km²), which we calculated following Ainley and Boekelheide (1983): number of animals sighted divided by area surveyed (transect width × segment distance). As we did not correct for detectability or other factors (see Pike *et al.* 2005), our dependent variable was actually an index to density rather than a true density estimate. We chose to model only the total density and presence/absence of any cetaceans (*i.e.*, all cetaceans detected regardless of species) seen on each transect because that provided us with the most data. Categorical independent variables used to model cetacean presence were as follows: (1) north or south of ACC southern boundary; (2) on or off the continental shelf; and (3) when south of the large-scale pack, in or not in a polynya (ice cover <10% within an area of significantly greater ice cover) (Table 1). Continuous independent variables were (1) date, (2) ice concentration (percent), (3) distance (km) to shelf-break front (1,000-m isobath), and (4) distance (km) to large-scale pack-ice edge (Table 1).

Table 1. Definitions and acronyms for covariates used to model whale presence/absence and whale density on transects in the Amundsen and Bellingshausen seas during autumn 1994.

Acronym	Definition
Date	Standardized by earliest Julian date
ACC	North or south of ACC boundary
POLY	For transects south of large-scale pack ice, they are inside or outside a polynya
SHELF	On or off the continental shelf
D_Ice	Distance (km) to unbuffered ice edge
D_MIZ	Distance (km) to marginal ice zone, defined by a 30-km buffer on either side of the ice edge
D_SB	Distance (km) to unbuffered 1,000-m isobath (shelf break)
D_600z	Distance (km) to shelf break zone, defined as area between the 600-m and 1,000-m isobaths.
Ice_g300	Ice concentration: percent cover within 300 m

To generate these covariates the survey data were plotted and analyzed using ArcGIS 9.1 (ESRI 2005). Bathymetric data for mapping were obtained from BEDMAP gridded data sets (Lythe *et al.* 2000). We extracted the 600-m and 1,000-m isobaths using the Spatial Analyst extension (ESRI 2005); the 1,000-m isobath was adjusted based on depth data from the ship's surveys. Confirmed by the CTD data, the Antarctic Slope Front occurred just seaward of the shelf break (*ca.* 600 m) and, therefore, the 1,000-m isobath in this region of very steep topography seaward of the shelf break served as a proxy for that front (see diagrams in Ainley *et al.* 1998). As a result, we could use that isobath to approximately locate the front even for ship tracks on which no CTD casts were made. We used the 600-m–1,000-m isobath to create a polygon representing an additional, different shelf-break zone (Table 1).

Ice cover was digitized from Ainley *et al.* (1998), in turn derived from real-time satellite imagery available on the cruise and also sea-truthed using survey data. We defined the “ice edge” as the MIZ, an area that includes 30 km on either side of the actual ice edge or where “water sky” or “ice blink” were obvious depending on whether we were in ice or open water (Ainley *et al.* 1998). The 30-km buffer is the area over which the actual ice edge fluctuates from day to day depending on wind direction; it is the melt water associated with this zone that is responsible for the increased productivity of receding or stationary ice edges that now interests marine biologists (Smith and Nelson 1985). Our definition of the MIZ also incorporates what is usually considered the ice edge in satellite studies, that is,, the large-scale margin of the 15% ice concentration (*e.g.*, Parkinson 2002).

We calculated the distances (km) from each survey point to the unbuffered shelf break and unbuffered ice edge using the *near* function in ArcToolbox (ESRI 2005). Distances (km) to the shelf break and marginal ice zones were determined using the AlaskaPak extension (NPS 2002) for ArcView 3.2.

Although we did quantify distance to these large-scale, ice-related, and depth-related features, we did not record the distance between the ship and the nearest ice within the census strip. Thus, we did not record lead width if we were in very heavy ice. Therefore, our density indices included the area of all open water and ice within a census segment. In the case of penguins and seals, which we were also counting, many occurred well back from the edges of leads or floes, and thus, we were looking for signs of life in those areas, too.

Data Analysis

The data collected, as is typical of cetacean surveys elsewhere, included a large number of transects on which no cetaceans were seen ($n = 475$). Therefore, we had to take this large number of “zero” observations into account in our analyses. Our detections were also biased low because, as noted, we did not correct for detectability and other factors that affect if a whale is seen, as would be the case if we were using line transects (*e.g.*, Pike *et al.* 2005). We chose to analyze these data in two pieces, similar theoretically to the “two-step” modeling approach advocated by Dobbie and Welsh (2001) and Cunningham and Lindenmayer (2005). We analyzed the presence/absence data (cetaceans present *vs.* not present on transect) using a logistic model, with variance structure blocked by Julian date and with an autoregressive variance structure to account for the autocorrelation and lack of dependence among survey segments

(Proc GENMOD; SAS Institute 1997). Survey transects within a particular day tended to occur sequentially or within ≤ 2 h between surveys. Owing to the fact that periods of daylight (when we could see well) were shorter than dark periods (but the ship traveled in the dark), survey segments within days were much more correlated in time and space than segments between days. Thus, Julian date seemed an appropriate way to structure the variances to account for the lack of independence between survey segments. As a block effect, Julian date was a categorical variable, but to investigate trends in cetacean presence/absence and density over time, we used an equivalent covariate standardized by earliest Julian date (*i.e.*, first survey occurred on day 46) as a continuous variable.

We modeled density (an index to whales/km²) using general linear modeling (Proc Mixed; SAS Institute 1997) for those survey segments on which cetaceans were sighted ($n = 42$). This approach allows modeling of the variance structure to account for any autocorrelation or lack of independence between survey segments in this reduced data set. We used restricted maximum likelihood estimation to examine a variety of variance structures including independent (within-subject error correlation is zero), unstructured, a first-order autoregressive, compound symmetric, banded Toeplitz structure, and log linear (Littell *et al.* 2002). The best variance structure turned out to be log linear with explanatory variables included from the best means model. This is consistent with what we have observed for other count data where variances increase with the mean (Dugger *et al.* 2005).

We used an information-theoretic approach (Burnham and Anderson 2002) to chose the best models for each analysis, including an initial stage where we determined the best variance structure for the whale density data (see above). This approach requires the development of an *a priori* model set and the use of Akaike's information criterion to find a best approximating model given the data and the model set. We developed *a priori* single-factor model sets that investigated the effect of all our covariates of interest (Table 1) for whale presence/absence and the whale density index. We used Akaike's information criterion corrected for small sample sizes (AIC_c), with delta AIC_c (Δ AIC_c) and AIC_c weights to aide in model selection following Burnham and Anderson (2002). Models with the lowest AIC_c were generally considered best, but the degree to which 95% confidence intervals for covariate coefficients overlapped zero was also used to evaluate competing models (Δ AIC_c < 2) and specific explanatory variables (Cooch and White 2006). Two-factor models combining categorical and continuous covariates were developed *a posteriori* if they seemed warranted based on initial model selection results.

The polynya covariate was only applicable on transects south of the large-scale pack-ice edge, so we could not include this covariate in the complete data set for presence/absence or whale density, as no missing data are allowed for comparisons of AIC_c. Instead, we re-ran the applicable models on the subset of the presence/absence data for which polynya data were available.

The cetacean density index was log transformed before modeling. The distance to various shelf-break variables and distance to ice edge (D_Ice) were all correlated, with $r \geq 0.65$ in each case, so we did not include more than one of these kinds of covariates in any of our candidate models. Distance to ice edge (D_ice) and D_MIZ were also very highly correlated ($r = 0.99$, $P = 0.0001$), so we used only D_MIZ in our modeling. The ACC categorical covariate was not included in the whale density model set, as whales were sighted on only one transect north of the ACC boundary (in itself a "result").

RESULTS

Sightings

We amassed 517 census segments over the course of 39 d when surveying was possible for at least part of the day (239.5 h total); total linear distance covered during surveys was 2,055 nmi or 3,494 km (Fig. 1). During this span we encountered minke whales on forty occasions, totaling 104 individuals. Minke whale group size ranged up to nine animals, but most sightings were of single whales (Fig. 2). However, in one group only five of twenty total individuals were within the transect strip. Minke whales contributed the majority of the sightings and the density index of minke whales was highly correlated with that of total cetacean density. We encountered killer whales on two occasions (totaling 35): 8 males, 12 females, and 4 juveniles in one, and 4 males and 7 females in the other. Presumably, although we were not aware of the categories at the time, these were of “type C” (Pitman and Ensor 2003) based on group size and the fact that they did not look any different from the hundreds of type C whales familiar to us in the southwestern Ross Sea (*e.g.*, Ainley 1985, Ainley *et al.*, 2006). We also saw two beaked whales of unknown species on one occasion and, off effort, two groups of sperm whales (*Physeter catodon*): seven in one and twelve in the other.

Relationship to Habitat Variables

The two best models contained D_MIZ (and slope front) and the additive effects of D_MIZ and ACC, respectively, and garnered almost all support *via* AIC_c weights for modeling the probability that whales were present on a survey segment (Table 2). Whale presence was best predicted by D_MIZ, with higher probability of whale presence farther into the pack ice (Table 2). In addition, the probability of sighting whales was also higher south of the ACC boundary (Table 2). In general, all models with covariates performed better than the intercept-only model except for models with D_SB or Shelf. However, for the best two-factor model including D_MIZ and the ACC boundary covariate there was conflicting information regarding the importance and strength of the effects. The confidence intervals for the coefficients denoting north or south of the ACC boundary did include zero ($\beta = 0.72$; 95% CI: -1.58 – 3.02), suggesting a weak effect. However, overall effect size (odds ratio = 0.34) was

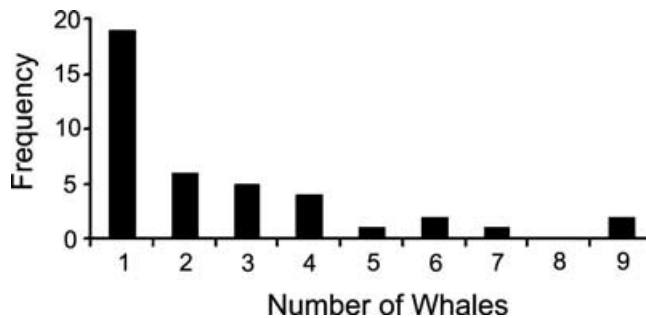


Figure 2. A frequency distribution showing group size of minke whales encountered during the cruise.

Table 2. Selection results for logistic regression models investigating the effects of oceanographic factors on the probability of whale presence in the Amundsen and Bellingshausen seas, autumn 1994. Small sample-size-adjusted Akaike's information criteria (AIC_c), the difference in AIC_c between each candidate model and the model with the lowest AIC_c value (ΔAIC_c), AIC_c weights (wt.), model deviance ($-2\log L$), and the number of parameters (k) are included for each model. Single-factor models were developed *a priori*, with two-factor models developed *a posteriori* after reviewing best single-factor models. The intercept-only model is also included for comparison. Covariate acronyms as in Table 1.

Model	AIC_c	ΔAIC_c	AIC_c wt.	$-2\log L$	k
D_Miz	283.46	0.00	0.53	279.44	2
ACC, D_Miz	284.27	0.81	0.35	278.23	3
ACC	287.69	4.23	0.06	283.67	2
Date	288.61	5.15	0.04	284.58	2
Ice-g300	292.86	9.40	0.01	288.84	2
D_600z	293.20	9.73	0.00	289.17	2
Intercept only	293.37	9.91	0.00	291.36	1
D_SB	294.76	11.30	0.00	290.74	2
Shelf	295.38	11.92	0.00	291.35	2

substantially greater than the effect size observed for D_MIZ (odds ratio = 0.997). The confidence limits around the covariate denoting D_MIZ did include zero when ACC was included in the model ($\beta = -0.0034$; 95% CI: -0.0072 – 0.0004), but did not when D_MIZ was the only covariate ($\beta = -0.0039$; 95% CI: -0.0071 – -0.0008). This suggested that D_MIZ was a more important effect than the ACC boundary covariate within the extent of our study area, but the increase in the overall probability of whale sightings farther into the pack ice was small. In general, the probability of seeing whales on any of these transects was very low (*i.e.*, whales were not observed on over 90% of transects). We believe this low probability, which is not unusual in cetacean surveys, is reflected in the overall effect size we observed in the covariates.

The analysis of the survey data south of the large-scale ice edge did suggest that the probability of sighting whales was increased in polynyas. This model had 67% of the total model weight, and 95% confidence intervals on the polynya covariate did not include zero ($\beta = 1.43$; 95% CI: 2.58 – 0.29) (Table 3). In addition, the odds ratio suggested this effect was quite strong (odds ratio = 0.24). There was some support for a polynya*date interaction—the probability of sighting cetaceans on transects in polynyas was highest early in the season—but the polynya main effect model received the strongest support (Table 3).

In contrast, unlike probability of sighting, the index to whale density was not directly related to D_MIZ or any of the continental shelf distance variables (Table 4). However, this is not surprising given the data used in this density analysis (*i.e.*, only transects with whales present) already reflects the “choice” whales have made to be south of the ACC and farther into the pack ice. Instead, ice concentration south of the large-scale ice edge had a strong negative influence on the index to total whale density ($\beta = -0.0233$; 95% CI: -0.0005 to -0.05): The density index was higher at lower ice concentrations, possibly reflecting the spatial realities associated with the number of cetaceans that can occur in pack-ice openings of varying size (*i.e.*, larger pack-ice openings required to hold higher whale densities) without affecting foraging

Table 3. Selection results for logistic regression models investigating the effects of oceanographic factors on the probability of whale presence on transects in the Amundsen and Bellingshausen seas, autumn 1994. Only survey segments south of the pack-ice edge are included in this analysis ($n = 393$). See Table 1 for covariate acronyms, and Table 2 for model set information and definition of column headings.

Model	AIC _c	ΔAIC _c	AIC _c wt.	−2LogL	<i>k</i>
Poly	245.72	0.00	0.67	241.69	2
Poly*Date	247.23	1.50	0.31	239.12	4
D_Miz	255.39	9.67	0.01	251.36	2
Date	255.44	9.72	0.01	251.41	2
Intercept only	256.21	10.48	0.00	254.19	1
D_SB	256.48	10.76	0.00	252.45	2
Shelf	256.63	10.91	0.00	252.60	2
D_600z	258.14	12.41	0.00	254.11	2
ACC	258.22	12.49	0.00	254.19	2

success. The single-factor model including ice concentration (ice_g300) received nearly 90% of the AIC_c model weight, so we did not investigate any two-factor models.

Whale Behavior

During the first portion of the cruise, until about 12 March, we often encountered minke whales and penguins associated with coastal polynyas (Fig. 1). Then the air temperature dropped noticeably, polynyas began to “steam” as the cooling water expelled heat and the exposed ocean began to freeze away from the areas where wind kept the polynyas ice-free. After the freezing began we noticed that all penguin tracks on floes or new ice headed north, and we thereafter almost never encountered either penguins or whales near the coast. We also observed holes in the newly formed ice that were punched by minke whales as they headed north (Fig. 3). Distance between the holes was 200–300 m. Penguins that were swimming, principally emperor penguins (*Aptenodytes forsteri*), which can hold their breath far longer than the diminutive Adélie penguin (*Pygoscelis adeliae*), but also the Adélie, used these holes to access both the ocean and the air.

Table 4. Selection results for linear models investigating the effects of oceanographic factors on whale density (whales/km²) in the Amundsen and Bellingshausen seas, autumn 1994. See Table 1 for covariate acronyms, and Table 2 for model set information and definition of column headings.

Model	AIC _c	ΔAIC _c	AIC _c wt.	−2LogL	<i>k</i>
Ice_g300	14.51	0.00	0.89	5.4	4
Intercept only	20.36	5.85	0.05	16.1	2
D_Miz	20.84	6.33	0.04	11.8	4
Shelf	23.71	9.20	0.01	14.6	4
D_600z	24.75	10.24	0.01	16.7	4
D_SB	24.92	10.40	0.00	16.8	4

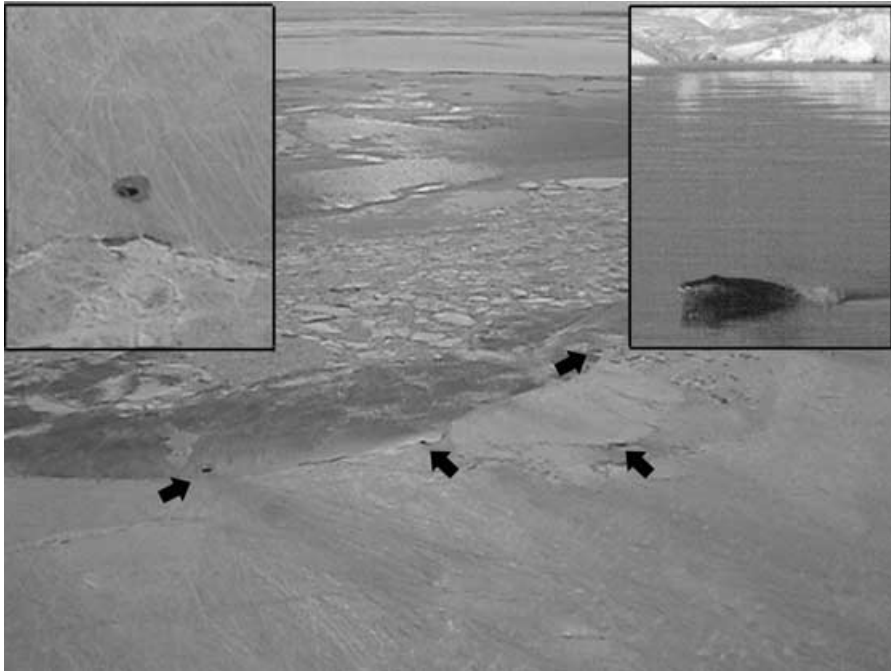


Figure 3. Aerial view of new ice formed adjacent to fast ice showing holes punched by the rostrum of minke whales. One inset shows a hole from a closer distance, and the other shows a rapidly moving minke whale surfacing through new ice that was several centimeters thick but still flexible.

In the open waters of the Ross Sea during the late 1970s (Ross Ice Shelf Project, RISP; Ainley 1985) minke whales vigorously avoided the ship, leaving behind a frothy wake and “porpoising” as they fled (Fig. 4). In the pack ice, on the other hand, this fleeing behavior was rarely observed. During the 1994 cruise reported here minke whales exhibited no fleeing behavior except when very near our ship in leads that were closing or otherwise narrow (Fig. 3). Fleeing behavior was never observed in killer whales.

DISCUSSION

As far as we know this report is one of the few to present results of cetacean surveys in what we call “the deep pack-ice zone of the Antarctic.” Most of our cruise was in the deepest pack ice, having penetrated repeatedly to 74°S , as far south of the marginal ice zone as possible and right to the coast. We were, at the time, one of the first cruises ever to visit Pine Island Bay as well as other portions of this region. We covered most of the region where the supposed eastern South Pacific minke whale stock occurs (see IWC 1991). Only Ainley (1985), who reported on cruises from the pack ice of the Ross Sea south to 77°S , presents the results of cetacean surveys that went farther south than the data presented herein. Thiele *et al.* (2000), Thiele and Gill (1999), and Shimada (*in* IWC, 2005) went as far as 67°S in East Antarctic seas;



Figure 4. The typical behavior of Antarctic minke whales, upon the approach of an ice breaker during surveys conducted in the Ross Sea during 1976–1980; December 1976, 300-mm telephoto lens.

Thiele *et al.* (2004) cruised to about 69°S off the Antarctic Peninsula; and Kasamatsu *et al.* (2000) surveyed waters north of the Amundsen and Bellingshausen pack-ice zone to about 70°S. All of the latter studies, except that by Thiele and Gill (1999) and Shimada (in IWC, 2005), surveyed the marginal ice zone and waters seaward of it (see also other MIZ studies, *e.g.*, Joiris 1991, Ribic *et al.* 1991, van Franeker 1992).

Minke whales, which comprise the bulk of our sightings, are small, cryptic, occur singly or in small groups, and surface for very short intervals and, therefore, detecting their presence can be difficult. We have no measure of whale detectability during these surveys so we must consider our density estimates as indices, with the potential for some unknown bias. However, Pike *et al.* (2005) reported nearly unbiased ship surveys for minke whales under optimal sighting conditions with high observer effort, with their effective strip width being 419 m. We believe our use of two observers scanning the same quadrant and the relatively narrow width of our survey swath significantly reduced the detectability bias in our index or at least made it equivalent for all survey segments.

We assessed the relative abundance of minke whales among reports in the readily available, refereed literature, relative to our results, by comparing sightings rather than true density estimates (which we could not make). The order of magnitude among sightings for all cruises was approximately similar. In ship-based surveys, sightings were most frequent in the Ross Sea during the 1970s–early 1980s; in the Amundsen/Bellingshausen seas in decades more recently they were more frequent on surveys within the ice (ours) than in those that mostly surveyed open waters north of the ice (Table 5). The Ross Sea surveys were conducted just after industrial whaling for minkes began and several years before its end, but whether the higher numbers seen by us during that period reflect a pre-exploited (undepleted) population level is not

Table 5. A summary of cruise effort and minke whales seen among high-latitude Antarctic cetacean surveys.

Area	Effort hours	Distance surveyed (km)	Survey type	Minkes seen (<i>n</i>)	Minke sightings (<i>n</i>)	Sightings/km × 100, divided by 1 vs. 2 sides of ship	Source
Amundsen and Bellingshausen seas	240	3,494	800-m strip, 1 side of ship; 1 cruise	104	40	11.4	This study
Amundsen and Bellingshausen seas	—	>7,000	Line transect, 2 ships; 2 cruises	—	76	~5.4	Kasamatsu <i>et al.</i> 2000
West Antarctic Peninsula	650	—	Line transect; 7 cruises	331	137	—	Thiele <i>et al.</i> 2004
Ross Sea	461	3,196	800-m strip, 1 side of ship; 3 cruises	153	78	20.5	Ainley 1985
West Ross Sea Polynya MIZ	8.1	298	Aerial, both sides	138	93	15.1	Leatherwood <i>et al.</i> 1982
East Antarctic seas	—	>7,000	Line transect; 1 cruise	98	48	~3.4	Thiele <i>et al.</i> 2000

known. In the Amundsen/Bellingshausen seas, our sightings of 104 minke whales on 40 occasions while scanning only to 800 m on one side of the ship compares favorably with 98 minke whales seen on 48 occasions by Thiele *et al.* (2000) while scanning to the horizon on both sides of the ship along more than double the total track distance of our cruise; an unknown number of whales but in low density (0.003–0.15 whales/km²) seen by Kasamatsu *et al.* (2000) on ~48 occasions during 1982–1983 and on ~28 occasions during 1989–1990 while scanning to the horizon on both sides of two ships, also over double our cruise track distance; and 137 sightings of 331 individuals seen by Thiele *et al.* (2004) over an undisclosed distance but scanning to the horizon on both sides of the ship on seven cruises (650-h effort). In the Ross Sea and waters directly north of it, on cruises during December and January 1976–1980, Ainley (1985) reported 153 minke whales seen on 78 occasions with two persons scanning to 800 m on one side of the ship over a track that was 3,196 nmi long (461 h). In an aerial survey in the MIZ of the western Ross Sea Polynya, Leatherwood *et al.* (1982) saw 138 whales in 93 groups along ~298 km of flight track (8.1 h).

The RISP cruises actually found relatively few minke whales in the central, completely ice-free portion of the Ross Sea Polynya where an appreciable amount of cruise effort was spent. The whales mostly frequented the MIZ that ringed this largest of all polynyas as well as the deeper pack ice, including smaller polynyas therein (Ainley 1985, Karnovsky *et al.* in press). During the *NBPalmer 94-2* cruise and that of Shimada, (in IWC, in press) the association of minke whales with small polynyas was consistent with the Ross Sea data. Karnovsky *et al.* (in press) explain that polynyas, specifically the large Ross Sea Polynya, vary in attractiveness to upper-trophic level predators and their prey due to variations in the dominance of different phytoplankters at the base of the food web.

We make the above comparisons to emphasize that the Antarctic minke whale is abundant in the deep pack ice of the Amundsen and southern Bellingshausen seas as well as in the adjacent Ross Sea. Their abundance in the deep pack ice elsewhere remains to be determined, but given that we have now looked in waters over more than one-third of the Antarctic circumference, it would be surprising if the pattern did not hold. The degree to which the IDCR/SOWER circumpolar surveys include what would be the pack-ice portion of the minke whale population (having moved from the pack) in its ensuing extrapolations is not known nor is it knowable on the basis of existing information (*e.g.*, Branch and Butterworth 2001). It is possible that these surveys, which occur between December and February, encounter the whales in some sort of southern/northern migration to/from the pack ice. However, judging from the results of Ribic *et al.* (1991), Thiele and Gill (1999), Thiele *et al.* (2004), van Dam and Kooyman (2004), and others, some portion of the Antarctic minke whale population remains in the pack ice, especially the MIZ, year round. In the southernmost reaches of the Ross Sea, minke whales arrive in early December (Ainley *et al.*, 2006) and probably depart, as they did during the current study, when the sea begins to freeze persistently in late February–early March. This freeze up was described by James Clark Ross (1847), whose expedition almost became trapped in late February, and by Roald Amundsen, whose ship, the *Belgica*, did become trapped in the ice of the southern Bellingshausen Sea in March 1898, ultimately being advected north and out of the ice by March 1899.

The killer whale type C (also B) appears to be a pack-ice species as well. The prevalence of killer whales in the Amundsen-Bellingshausen pack ice was comparable to the Ross Sea pack ice: our cruise tallied two sightings of thirty-five animals compared to the six sightings of sixty-four animals reported in the Ross Sea by

Ainley (1985). In studies of the MIZ, Thiele *et al.* (2000) obtained 14 sightings of 43 animals off East Antarctica, and Thiele *et al.* (2004) had 17 sightings of 172 animals off the western Antarctic Peninsula. In the southern Ross Sea, type C killer whales arrive a few weeks before the minke whales and seemingly depart at about the same time (Ainley *et al.*, 2006). Farther north, killer whales occur in the pack ice, especially associated with polynyas, also during the winter (Thiele and Gill 1999, van Dam and Kooyman 2004).

The fact that the vast majority of the whales we encountered were south of the ACC southern boundary, but not at the boundary as if it were a “front” of enhanced ocean production, was a pattern also observed by Thiele *et al.* (2000, 2004), and on the basis of the findings of Tynan (1998) and Nicol *et al.* (2000) should come as no surprise. The waters south of that boundary are far richer than those to the north. South of the ACC boundary and during the first part of our cruise when ice cover was less extensive, whales coincided with coastal polynyas/postpolynyas but not necessarily with the Antarctic Slope Front (*e.g.*, Ainley and Jacobs 1981, Massom *et al.* 1998, Thiele and Gill 1999, Ainley 2002, Friedlaender *et al.*, 2006). Unfortunately, the slope front coincided with the MIZ during our cruise and, thus, it was not possible to assess the relative importance of each independently. Interestingly, once the ocean surface within the pack began to consistently freeze, the divergent ice of the MIZ/slope front became the feature most associated with minke whale abundance (see also Ribic *et al.* 1991; Thiele *et al.* 2000, 2004; Friedlaender *et al.*, 2006). As evident in our model of the density index, once within the MIZ (as indicated by the presence/absence analysis), the density of whales increased farther from the ice edge. Whether that had to do with actual increased prey availability due to the slope front or the simple spatial fact that lower ice concentrations result in larger openings that can hold more whales (without affecting foraging success), remains to be determined.

Therefore, it is clear that seasonal changes in the ice pack strongly affect the habitat preferences and occurrence patterns of Antarctic minke whales (and perhaps killer whales, type C). Branch and Butterworth (2001) are on the right track in questioning whether the changed timing of recent IDCR/SOWER cruises has affected analysis results. On the basis of the patterns described herein and the documented dramatic, decadal-scale changes in sea-ice patterns, which vary on a regional basis (*i.e.*, reduced ice extent, more divergent ice, and a shorter sea-ice season in the Amundsen to Scotia sea sector but more ice, a longer season, and larger polynyas in the Ross Sea and east Antarctic sectors, see Parkinson 2002, Zwally *et al.* 2002), it is highly possible that the results of the IDCR/SOWER analyses have been affected as well (Branch and Butterworth 2001; see also Ainley *et al.* 2005). If surveys are conducted mostly in open waters, more extensive ice means that less of the water south of the ACC southern boundary can be surveyed; and larger polynyas in areas of more extensive ice mean that more whales would be inaccessible. In the Bellingshausen region, ice extent and concentration have declined during recent decades (Zwally *et al.* 2002), and thus more minke whales might be occurring south of the large-scale ice edge. Apparent population trends would be least affected by sea-ice change along the coast of East Antarctica and the northwest coast of the Antarctic Peninsula, both areas that historically have become mostly ice free during late summer and autumn. Besides the possible effects of changed sea ice, Branch and Butterworth (2001) speculate on other factors that could be responsible for apparent changes in minke whale abundance on the basis of the most recent minke whale Antarctic-wide surveys. However, we have no basis here to be adding to that speculation.

Given the results of our cruise and analysis, a number of secondary questions arise. First, have Antarctic minke whales always preferred the deep pack ice or has this characteristic been selected by the intensive cropping of individuals occurring in more open water during the industrial whaling of the 1970s and 1980s (~~40% of total population removed; Branch and Butterworth 2001~~)? Second, was the “flighty” behavior characteristic of whales seen in open water during the late 1970s (RISP surveys; Ainley 1985) a result of the whaling? Third, if Antarctic minke whales have always exhibited a pagophilic affinity, then is it not unlikely that their abundance now has little to do with the slow recovery of blue whales (*B. musculus*; Kawamura 1994)? The latter frequent the continental slope and outer MIZ (Thiele *et al.* 2000, 2004) and, therefore, many Antarctic minke whales occur in a habitat where blue whales do not. However, fifth, might foraging by the blue and other large whales have encouraged the pagophilic nature of the Antarctic minke whale? In that regard, it is interesting that both Ross (1847) and Amundsen (1913) noted blue and fin (*B. physalus*) whales in the vicinity of the Bay of Whales (extreme eastern corner of Ross Sea, between the ice pack and Ross Ice Shelf), where today only large numbers of minke whales occur (see discussion of whale competition in Thiele *et al.* 2000; Friedlaender *et al.*, 2006). Finally, is it not possible that the high abundance of Antarctic minke whales today relative to the low abundance of the great whales was facilitated by a significant portion of the population remaining in the pack ice and inaccessible to whalers? There are about seven ice “refuges,” that is, areas that are ice covered year round, that exist around the Antarctic circumference (see maps in Gloersen *et al.* 1992); these were never accessible to whaling ships.

The pagophilic nature of the minke whale is most similar to that of emperor and Adélie penguins and various pack-ice seals (Ainley *et al.* 2003). The whale’s relatively greater size allows it to break breathing holes in the newly forming ice, thereby providing an important symbiotic “service” to other air-breathing and diving species that inhabit the pack ice and MIZ. Most of these predators also compete for the same food source, so significant seasonal and longer-term changes in abundance of any one species potentially could affect that of other members of this guild (Ainley *et al.*, 2006).

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