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Winter distribution and abundance of crabeater seals off George V Land, East Antarctica

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Abstract: This study is the first to describe the winter distribution of crabeater seals (*Lobodon carcinophagus*) in East Antarctica. The study was conducted in the Mertz Glacier Polynya region from July to August 1999. In total 89 crabeater seals were seen in 26 groups which ranged in size from 1 to 35 animals (mean = 3.2). The mean observed haulout density along a 200 m wide strip transect was 0.108 seals per km^2, or 0.042 groups per km^2. Crabeater seals were not uniformly distributed in the polynya but selected areas of stable ice over shallow (< 1000 m) waters. We used a generalized linear model to assess the relationship of seal distribution to the physical attributes of sea ice concentration, thickness, and ocean depth. We found that ice thickness and ocean depth were the most important determinants of seal distribution. Crabeater seals occurred in areas where the ice affords them a stable haulout platform while allowing them access to Antarctic krill that live directly beneath the ice.

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Introduction

Crabeater seals, *Lobodon carcinophagus* (Hombron & Jaquinot, 1824), are believed to be the most ubiquitous seals in the world, with an estimated population of 11–70 million seals (Erickson & Hanson 1990, Gilbert & Erickson 1977, Siniff *et al.* 1970). These estimates are based on large-scale extrapolations and limited reference to the haulout behaviour of the seals and must be treated cautiously. Crabeater seals are confined to the pack ice and can be found anywhere south of the Antarctic Polar Front (APF) where there is suitable ice (Kooyman 1981). The pack ice provides the necessary platform on which the seals moult, breed and haul out to rest. In winter the pack ice covers an area of up to 19 million km^2, and shrinks to *c.* 3–4 million km^2 in summer (Gloersen *et al.* 1992). Crabeater seal densities and distributions may therefore be expected to vary seasonally in any location.

Crabeater seals are an important component of the krill-based food chain in Antarctica because of their abundance and because they feed predominantly on krill, consuming an estimated 72 x 10^6 tonnes per annum (Laws 1984). However, despite the ecological importance of this abundant species, little is known about its seasonal distribution and density. This is due to the practical difficulties of conducting surveys in the Antarctic sea ice zone, especially in winter. Most surveys have therefore been restricted to the summer months (December to March) when ice extent is at a minimum, reducing the survey difficulties. Previously, only a few studies have commented on the distribution of crabeater seals in winter (Bester 1979, Ribic *et al.* 1991) and only one study has described the diving behaviour of these seals in winter (Nordoy *et al.* 1995).

The pack ice zone of the Southern Ocean comprises a variable concentration and heterogeneous mixture of ice of various types, with ice thickness depending not only on its age but also the degree of deformation (i.e. ridging and rafting) (Massom *et al.* 1999, Worby *et al.* 1998). Related key biological factors are ocean upwelling, variable ocean depth and variable primary productivity. Krill are known to respond to changes in these habitat characteristics, and because crabeater seals feed primarily on krill, it is likely that the seals will respond similarly. Crabeater seal densities and distributions in winter may therefore act as indicators of local krill aggregations.

This paper reports on the distribution of crabeater seals in the Mertz Glacier Polynya (MGP) region of East Antarctica between July and August 1999, and relates this to physical characteristics such as ocean depth and sea ice parameters (including ice thickness and degree of deformation).

Methods

Seal data collection

Surveys were carried out off George V Land (East Antarctica) between 62°–67°S and 143°–147°E in July and August 1999. Observers were present in all daylight hours and opportunistic observations were also made during the night. As this was not a dedicated seal survey, but rather an oceanographic voyage,

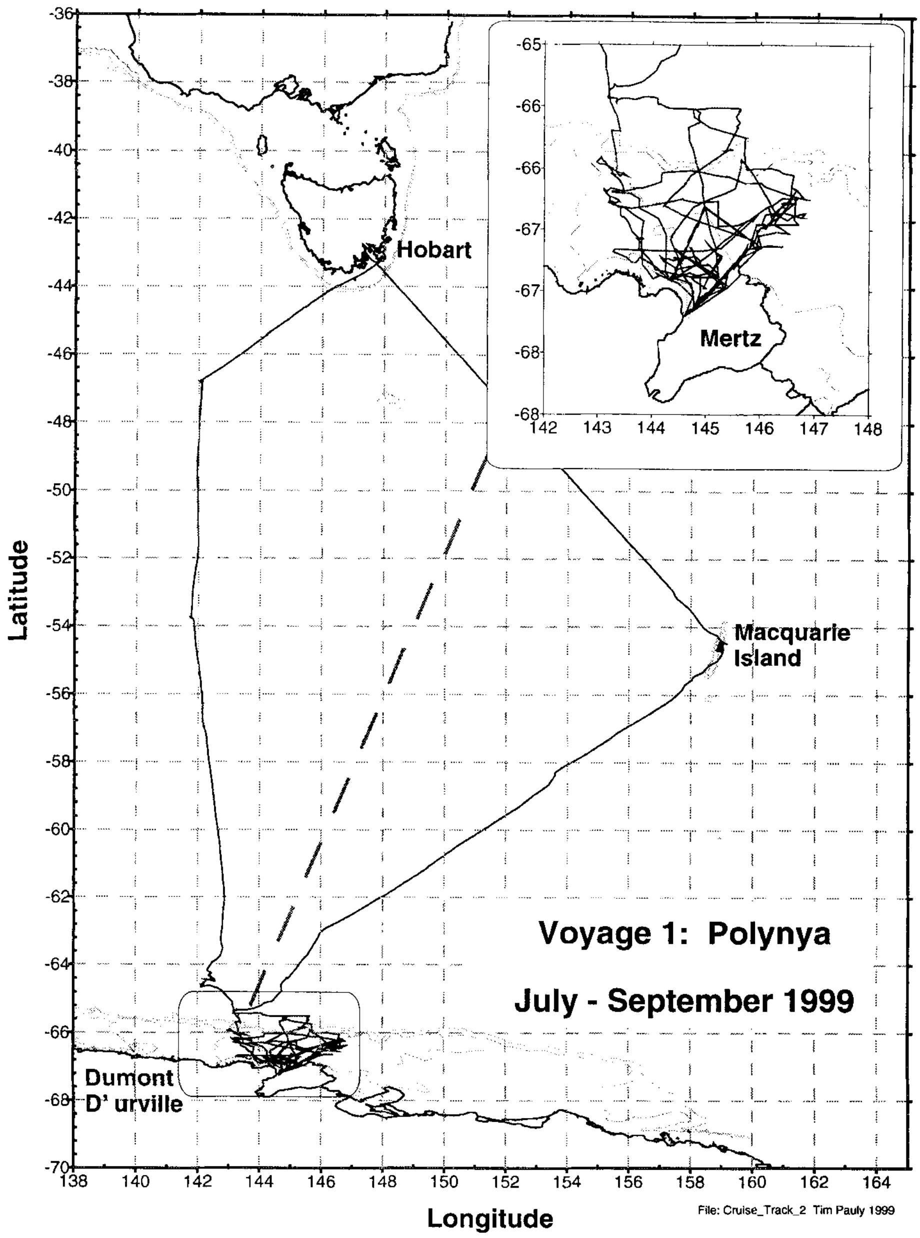

Fig. 1. Cruise track of the RV *Aurora Australis* during the 1999 winter to the Mertz Glacier Polynya region. Latitude is shown in °S, longitude in °E.

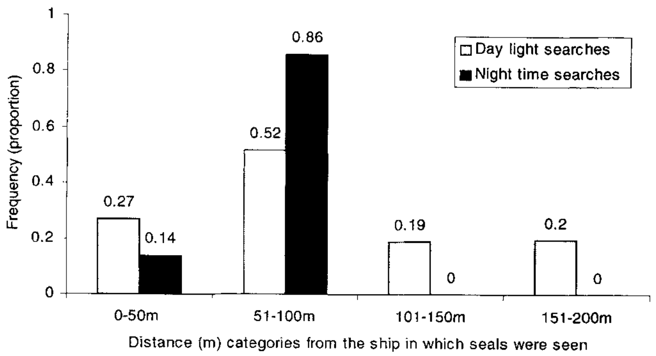

Fig. 2. The frequency distribution of distance (m) categories for seal sightings during daylight surveys and during night-time surveys from the RV *Aurora Australis*.

the ship's track did not follow a regular search pattern (Fig. 1). Counts of seals were made from the bridge of the icebreaker RV *Aurora Australis* and the distance of all seals either side of the bridge (18 m above sea level) was recorded. For statistical analyses, only seals seen within 100 m either side of the ship were included. This was the maximum reliable distance that could be surveyed with the ship's searchlights on either side of the vessel, and no seals were seen beyond this distance at night (Fig. 2). Observers searched continuously on both sides of the ship when weather permitted. Watches were only abandoned when visibility was below 50 m. When seals were sighted, group size, distance from the ship, sea ice characteristics, and time were recorded. The position of the ship was recorded every 30 min, from a global positioning system.

Seal density estimates

The survey area and ships track was overlaid with a 0.5° latitude and longitude grid. The seal data were then expressed as the number of seals seen per kilometre travelled for each 0.5° grid square. The 0.5° grid squares were used to reduce spatial dependence in the data.

Sea-ice data collection and analysis

Information on sea ice (and snow cover) thickness and characteristics, such as degree of rafting, percentage ice cover and ice type, was routinely collected by visual hourly observations while the ship was underway, using a standardized technique (Worby & Allison 1999), and by detailed on-ice sampling at 42 ice station locations. The hourly observation data included estimates of sea ice type (WMO 1971), concentration, floe size distribution and degree of deformation (ridging and rafting). Larger scale sea ice distribution characteristics were determined from analysis of digital aerial photography and satellite data. The latter included NOAA Advanced Very High Resolution Radiometer (AVHRR) thermal infrared data collected at Casey, and Radarsat synthetic aperture radar (SAR) data processed by the NASA Alaska SAR Facility. The satellite data were interpreted by comparison with surface observations. Information on the ice edge location was derived from sea ice concentration data collected by the DMSP Special Sensor Microwave/Imager (SSM/I). A detailed analysis of sea ice conditions in the region, and the dynamics of the Mertz Glacier Polynya are contained within Lytle *et al.* (2001) and Massom *et al.* (2001). A detailed description of the regional oceanography, including the bathymetry, appears in Bindoff *et al.* (2001).

Environmental correlates of seal distribution

The relationship between the physical characteristics of the environment and the number of seal groups per 0.5° grid square was determined using the GENMOD procedure in SAS 6.11, with a Poisson error model and a log link (McCullagh & Nelder 1989). As the number of groups seen was a function of the distance travelled within the grid, we also used the log of distance travelled within each grid as an offset in the model. Three variables were included in the full model (ice thickness, ocean depth and percentage ice cover). We calculated an average value for each of the three variables in each of the 44 grids cells that the ship traversed, and used these means in the model. The percentage data were arcsine transformed before analysis. The model was therefore:

$$\mathrm{Log}\,(n) = \mathrm{Log}\,(L) + a + (b_1{*}T) + (b_2{*}D) + (b_3{*}P)$$

where n = the number of seal groups, L = total distance travelled in the grid, D = depth, P = % ice cover and T = ice thickness.

The most parsimonious model was determined by removing variables in a stepwise fashion, and assessing the change in deviance using χ_2 comparisons.

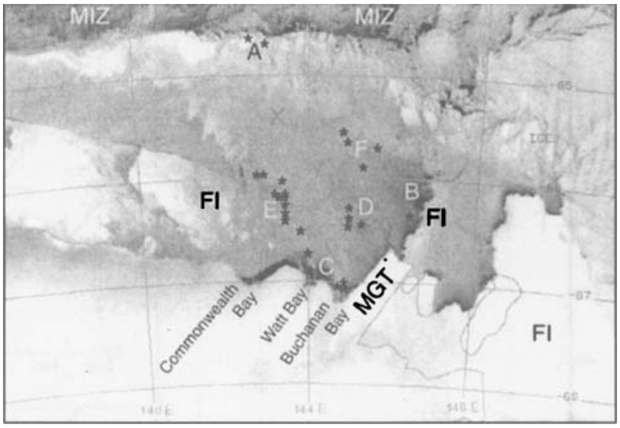

Fig. 3. The distribution of crabeater seals in the Mertz Glacier Polynya region in relation to general ice zones within the study area between July and September 1999. The locations (A–F) are marked on an AVHRR channel 4 (thermal infrared) image from 14 June 1999 (16:57 UTC). This image courtesy of the Australian Bureau of Meteorology. FI refers to fast ice, MIZ refers to marginal ice zone and MGT the Mertz Glacier tongue.

Results

The ship spent 40 days in and around the polynya region, covering a total distance of 4670 km. During this time, 89 individual crabeater seals were seen, 77 of which were within the 200 m transect. The mean observed haulout density along the 200 m wide strip transect was 0.108 seals per km^2. Crabeater seals were seen singularly or in small groups varying between 2 to 35 seals (median = 3 seals, mean = 3.10, n = 23). The largest group of seals seen consisted of 35 seals. The density of groups was 0.042 groups per km^2.

The map of the distribution of crabeater seal sightings, superimposed on an AVHRR channel 4 (thermal infrared) image, shows the broad-scale sea-ice characteristics of the region (Fig. 3). Massom *et al.* (2001) identified a number of distinctive zonal sea-ice regimes based on analysis of the satellite data validated by contemporary surface observations. From north to south, these are:

1. An outer pack regime, or marginal ice zone, where wave–ice interaction processes predominate and the floe size is comparatively small (compared to the inner pack, where ocean swell is typically damped) and the concentration relatively low. This zone also occurs outside the shelf break in winter. In Fig. 3, this zone (marked MIZ) extends from *c.* 61° to *c.* 64.6°S along the 145°E meridian. During the survey, the ice edge location varied from *c.* 61° to 63° S.
2. Immediately to the south, there was a 50–100 km wide

"stream" or band of very thick ice (2 to *c.* 5–10 m thick, with a 1–2 m thick snow cover), advecting from the region to the east and deflected to the north of the MGP by meridional blocking features (in the form of grounded bergs and fast ice). Comprising the lighter coloured horizon in the satellite image (Fig. 3), this zone extended from *c.* 64.6° to 65.5°S down the 145°E meridian. It effectively separated the outer from the inner pack, and roughly follows the shelf break.

3. To the south was a zone of sea ice formed in the polynya, which acted as a significant "sea ice factory" for the region (Lytle *et al.* 2001, Massom *et al.* 2001). This polynya comprises two different regimes: i) one to the south, and extending from Commonwealth Bay to Buchanan Bay, which is associated with strong and persistent katabatic winds (the "katabatic poloynya", and ii) another along the western margin of the Mertz Glacier tongue and its associated extension of grounded bergs and fast ice, associated with prevailing easterly/ south-easterly synoptic winds in the near-shore zone (Massom *et al.* 2001). In both cases, strong winds remove sea ice from the region as quickly as it forms, and largely maintain regions of open water/thin ice or low ice concentration. While the polynya proper is restricted to a relatively narrow coastal zone, ice formed there supplies much of the surrounding region i.e. the darker grey region in Fig. 2 where most of the seal sightings occurred. Based upon contemporary drifting buoy data, ice formed in the polynya drifts predominantly to the north-west, thickening with distance from the polynya by both thermodynamic growth and deformation processes (ridging and rafting).

The regional sea ice regime, and behaviour of the polynya, is further complicated by the presence of areas of annual fast ice (marked FI on Fig. 3), both extending out from the coast to the west of the polynya and as a "finger" extending northwards from the terminus of the floating Mertz Glacier tongue. In both cases, the fast ice is "pinned" in place by lines of icebergs which are grounded on shoals 200–300 m deep (Massom *et al.* 2001).

Table I. Summary of the distribution of all crabeater seals seen in the Mertz Polynya region between July 1999 and September 1999, and a brief description of the ice characteristics of each region.

Seal group from Fig. 3	*n*	Ice (habitat) characteristics
Group A	4	Stable consolidated ice, no leads, ocean depth > 2000 m.
Group B	11	Stable new ice, with leads and cracks.
Group C	7	Stable new ice consolidating to 0.15 m thick, with leads and cracks.
Group D	9	Stable new ice consolidating to 0.40 m thick, with leads and cracks.
Group E	41	Stable compact 1st year ice to 0.80 m thick, with cracks.
Group F	17	Stable 1st year ice to 0.50 m thick, with cracks.

Within the context of these broad-scale regimes, certain relationships are apparent between seal distribution and sea-ice characteristics. Primarily, no seals were sighted in the outer pack, or marginal ice zone (Table I). The northernmost sightings (marked A on Fig. 3, in the vicinity of 64.6°S, 142–143°E) coincide with the equatorward boundary of the inner pack, where more consolidated and stable sea ice conditions occur. These two groups of sightings are effectively outliers, with the majority of the sightings occurring within the MGP regime to the south. Crabeater seals were encountered most often in an area of consolidated (high concentration) sea ice to the north of the MGP (Fig. 3).

Further comparison suggests that different seal groups are associated with different sea ice conditions within and around the polynya regime. To the north-east, the grouping marked B is associated with regions of new ice formation in the polynya adjacent to the "finger" of fast ice and the fast ice itself, which constitutes a very stable haulout substrate. In addition to the seals, large concentrations of Adélie and emperor penguins were encountered in this area, together with four minke whales. The water here is *c.* 200–300 m deep.

To the south, group C occurred on the outer margins of "katabatic polynya", where newly-forming ice was consolidating to a thickness of *c.* 0.15 m. No seals were encountered in the open water region proper here, as conditions were turbulent and dominated by unconsolidated frazil ice. Group D was also associated with a consolidating ice cover (0.15–0.40 m thick, consisting of floes ranging from 20–500 m in diameter), but further from the coast.

To the north-west, group E occurred in a zone of highly compact first-year ice, 0.4–0.8 m thick with a 0.1–0.2 m thick snow cover and comprising floes 100–2000 m across separated by narrow (< 50 m) cracks. The ice cover was characterized by heavy ridging, covering 40–50% of the ice surface area and with sails 1.0–1.5 m high, due to the blocking presence of the fast ice promontory (Massom *et al.* 2001). The relative biological richness of this area was mirrored in the large numbers of Adélie penguins encountered. Again, the ocean depth is relatively shallow (200–500 m).

Finally, group F occurs in a region of predominantly first-year ice to 0.5 m thick. In this area, vast floes (500–2000 m in diameter) were separated by narrow leads (50–200 m across). One major difference compared to groups A–E is that group F sightings occurred over the shelf break in waters to a depth of 2000–2500 m. The relative paucity or absence of seal sightings in the regions marked X, Y and Z may be associated, amongst other things, with the presence of relatively deep water basins or troughs.

The most parsimonious model describing the distribution of crabeater seals in our winter study was the one incorporating ice thickness and ocean (Table II). The deviance/degrees of freedom ratio of close to one indicates an overall good fit to the model. The parameter estimates indicate that the number of groups of seals was negatively related to ocean depth, but positively related to ice thickness. Therefore, crabeater seals

Table II. Results of the generalized model relating number of groups of seals to three environmental variables, ice thickness, ocean depth and percentage ice cover. The most parsimonious mode is the model 2 (italicized), and any further removal of variables resulted in a significant change in the deviance.

			Estimate				
Model	Deviance	Dev/df	Depth	% ice	Ice thickness	Dev diff	χ^2
1	62.6	1.64	-0.0007	0.201	1.39	0.01	0.920
2	*62.6*	*1.61*	*-0.0007*		*1.41*	*6.48*	*0.011*
3	69.1	1.72			0.857		

were most commonly encountered in areas over deep water where the ice was thickest.

Discussion

This study represents the first survey of crabeater seals in East Antarctica during winter. Previous studies in summer (Bester *et al.* 1995, Condy 1976, Erickson & Hanson 1990, Gilbert & Erickson 1977, Siniff *et al.* 1970, Wilson 1975) and winter (Ribic *et al.* 1991) have, when relating crabeater seal distribution to environmental features, concentrated on sea ice cover as the chief predictor of crabeater seal distribution and abundance. However, the results of these studies were often conflicting, with some reporting no correlation (Bester 1979), a positive correlation between seal abundance and ice cover late in the season (Bester *et al.* 1995, Condy 1976, Wilson 1975), or no correlation early in the season (Bester *et al.* 1995) while others reported a negative relationship between ice cover and seals abundance (Siniff *et al.* 1970). This would suggest that large-scale extrapolations (generalizations) from surveys over relatively small areas may not provide an accurate assessment of the distribution of seals in general.

The sea ice in the region of the Mertz Glacier between July and August 1999 was a complex mixture of several distinctive ice regimes. These regimes ranged from open water within the polynya proper to very thick solid, multiyear ice. The pack ice was highly dynamic, with the outer ice edge location changing (advancing) by over 200 km in the course of the study. The crabeater seals observed during the study did not use all of these ice regimes equally. The least utilized was the marginal ice zone, where deep water and ice made more unstable due to wave action predominated, or within the polynya itself where ice was insufficiently thick to act as a haulout platform. Most of the seals were sighted in ice regimes characterized by older, more stable ice, but where leads allowed the seals access to the water. Our observations are similar to those made during winter in the Scotia and Weddell seas (Ribic *et al.* 1991). The other common characteristic associated with most seal sightings was that they were in the relatively shallow water (i.e. less than 1000 m) over the continental shelf where the ice was thickest. The dominant factors responsible for this thickening are sea ice advection across and out of the region and dynamic thickening by the synoptic scale processes of cyclical convergence and divergence (Worby *et al.* 1998).

Although the ice in this study may be atypical due to the presence of the glacier and the resultant polynya, these observations nonetheless indicate that crabeater seals are not uniformly distributed throughout the winter pack ice, but rather respond to certain physical characteristics. The seals may exhibit these preferences for several reasons. One is that the seals prefer the stable platform afforded by thicker ice, and the easy access to the water made available through the larger number of leads. Alternatively, or perhaps in addition, this type of ice may be a richer source of prey than other types of ice.

Food availability during the winter is likely to be to be the ultimate determinant of seal distribution because adults will have to meet the complex energetic requirements of:

i) maintaining body temperature at the coldest time of the year,

ii) increasing fat reserves for the breeding season, and

iii) gestation (for females).

In winter, phytoplankton aggregations are restricted and occur almost entirely directly under ice. Therefore krill, the predominant prey of crabeater seals, also live directly below the ice (Siegel *et al.* 1990). Previous studies (Hosie *et al.* 2000, Ichii 1990) have shown that during summer, krill occur most commonly in close proximity to the 1000 m isobath around the Antarctic coast. Although little is known of the abundance and distribution of krill in winter, it has nonetheless been suggested that they are most abundant in waters < 1000 m deep (Kirkwood & Robertson 1997). It is in this region, close to the 1000 m isobath, that we found the greatest concentrations of crabeater seals during winter.

The number of crabeater seals (89) seen during this study was relatively low compared to surveys conducted elsewhere during summer and autumn (Erickson & Hanson 1990, Erickson *et al.* 1971, Gelatt & Siniff 1999). The observed haulout density of individual seals from our study was 0.108 seals per km^2. Although this estimate needs to treated with caution, because it was derived opportunistically during an oceanographic study rather than from a dedicated seal survey, this figure is an order of magnitude less than the 1.0 seal per km^2 reported by Erickson *et al.* (1971) in the Weddell Sea, and 1.74 seals per km^2 in the Ross Sea (Ray 1970), but similar to the 0.76 seals per km^2 in the Amundusen–Bellinghausen seas (Gelatt & Siniff 1999). Previously, it had been hypothesized that crabeater seal densities may decrease in winter, due to increase in total area covered by pack ice, and therefore an increase in available habitat. However, the results of our study indicate that not all of this pack ice zone is suitable habitat for crabeater seals during winter. Rather, the seals may still concentrate in regions offering a suitable combination of ice conditions and prey availability. Therefore, the relatively low density of seals seen during this study may not have due to the increased amount of winter pack ice, but rather due to the relatively low productivity of this area. In general, the waters of East Antarctica have lower abundances of krill than more productive regions such as the Weddell Sea and the Antarctic Peninsula (Nicol *et al.* 2000).

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