NOAA Technical Memorandum NMFS-AFSC-64

Characterization of Oceanographic Habitat of Cetaceans in the Southern Indian Ocean Between 82° - 115° E: Cruise Report from World Ocean Circulation Experiment (WOCE) I8S and I9S

by
C. Tynan

U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
National Marine Fisheries Service
Alaska Fisheries Science Center

July 1996

NOAA Technical Memorandum NMFS

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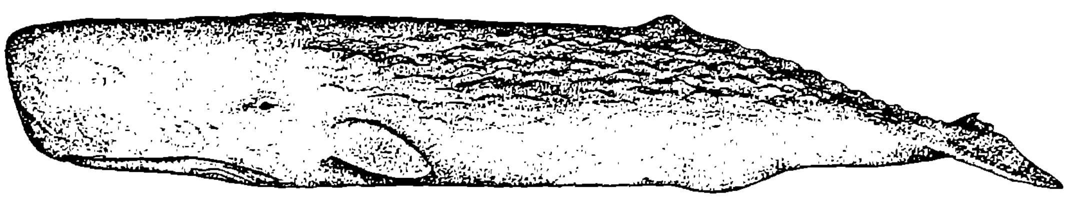

Sperm whale (Physeter macrocephalus)

by
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July 1996

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ABSTRACT

Cetacean surveys were conducted aboard the R.V. Knorr during World Ocean Circulation Experiment (WOCE) hydrolegs 18S, 19S in the Southern Indian Ocean from December 1, 1994 to January 19, 1995. A total of 186 sightings of cetaceans were obtained. Sperm whales (Physefer ***macrocephalus)*** were the most numerically abundant large cetacean south of the Polar Front. Sperm whales occurred directly over or in close proximity to complex bathymetry, such as the southeast edge of the Kerguelen Plateau. ***Minke*** whales ***(Balaenoptera acutorostrata)*** were the second most numerically dominant species. Eighty-five percent of minke whale sightings were recorded south of 60°S near the retreating ice edge. The highest density of minke whales occurred along the eastern flank of the Kerguelen Plateau, along a tongue of ice advected northward with the western boundary current. Migrating humpback whales ***(Megaprera novaeangliae)*** were observed as far south as the retreating ice (64°S). Over 50% of the humpback whale sightings were associated with the Kerguelen Plateau.

The highest density of cetaceans was observed along the southern flank of the Kerguelen Plateau. This distribution aligned with the mean position of the Southern Front of the Antarctic Circumpolar Current (ACC) and the southern water mass boundary (Southern Boundary) of the ACC. In this region the mean positions of ‘the Southern Front and Southern Boundary of the ACC are similar to the pattern of ice retreat, due to the topographic steerage of currents around the Kerguelen Plateau and the presence of a western boundary current. The combination of complex bathymetry, high latitude penetration of the Southern Boundary of the ACC, shoaling of nutrient-rich, warm Upper Circumpolar Deep Water (UCDW) at the Southern Boundary, the presence of the marginal ice zone, and the pattern of ice retreat, generates uniquely favorable conditions for cetaceans at the southeast comer of the Kerguelen Plateau. Further, in this region the Southern Boundary of the ACC and the Antarctic Divergence occur in close proximity, enabling subsurface nutrient-rich UCDW to be upwelled or entrained into the surface mixed layer. Cetaceans may benefit from the cascade of trophic dynamics reliant on the nutrient enrichment from shoaled UCDW at high latitude and the productivity of the marginal ice edge.

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INTRODUCTION

In December and January of 1994-1995, the National Marine Mammal Laboratory (of the Alaska Fisheries Science Center, National Marine Fisheries Service, National Oceanic and Atmospheric Administration (NOAA)) participated in a cruise of the World Ocean Circulation Experiment (WOCE) in the Southern Indian Ocean. WOCE is a U.S. program designed to investigate the circulation and physical-chemical properties of the oceans of the world. In 1994 and 1995, WOCE focused its effort in the Indian Ocean. Table 1 summarizes the measured parameters, contributing institutions, and personnel for the WOCE program. The author organized and coordinated marine mammal and seabird surveys during the cruise. Three experienced observers were contracted by NOAA for the cetacean and seabird survey: Richard Rowlett, James Cotton, and Robert Pitman: This cruise report contains the results of the cetacean survey, an analysis of cetacean habitat in the Southern Indian Ocean, and a discussion of the important oceanographic processes associated with preferred cetacean habitat in the Southern Ocean. Sightings of pinnipeds are included in the report, although the survey design was not intended for this purpose. The results of the seabird surveys will be treated in a separate report.

The objective of our-survey was to characterize the oceanographic habitat of resident and migratory species of cetaceans in the Southern Indian Ocean from Fremantle, Australia, to the ice-edge, between 82°-115°E. In this region, populations of baleen whales fall into “Group IV” or ‘the Antarctic Area IV, between 70°E and 130°E; sperm whales and other odontocetes fall under divisions 4 and 5, between 60°-90°E and 90°-130°E, respectively (International Whaling Commission, 1995). A secondary objective was to examine the physical oceanographic processes which contribute to enhanced cetacean densities in a well-defined region, in order to explain cetacean distributions on a larger circumpolar scale.

Table l.-Summary of WOCE oceanographic measurements and personnel.

Parameters	Contributing Institutions	Personnel
CTD-O_2 rosette	Woods Hole Oceanographic Institution (WHOI)	M. McCartney, T. Whitworth
Salinity, oxygen	WHOI	M. McCartney, T. Whitworth
Nutrients	Oregon State University (OSU)	L. Gordon
CFCs, Carbon tet.	Lamont-Doherty Earth Observatory (LDEO)	W. Smethie
	Pacific Marine Environmental Laboratory (PMEL)	J. Bullister
Helium, Tritium	LDEO WHOI	P. Schlosser, W. Jenkins
Radiocarbon	Princeton	R. Key
ADCP, LADCP	U. Hawaii	E. Firing, P. Hacker
ALACE floats	Scripps Institution of Oceanography (SIO)	R. Davis
Barium	OSU	K. Falkner
Total carbon	Brookhaven National Laboratory (BNL)	D. Wallace
Alkalinity	BNL	D. Wallace
Thermosalinograph(FSI)	WHOI	B.Walden
Bathymetry(SEABEAM)	WHOI	B.Walden
Meteorology(IMET)	WHOI,Princeton	B.Walden, C.Sabine
Air chemistry	PMEL	J. Bullister
Underway pCO_2	BNL	D. Wallace

WOCE I8S, I9S Cruise Participants

Michael McCartney	WHOI, Co-Chief Scientist
Thomas Whitworth III	Texas A & M Univ. (TAMU), Co-Chief Scientist
Eric Firing	U. Hawaii ADCP specialist
Marshall Swartz	WHOI CTD team leader, Watch leader
Steven Rutz	TAMU CTD watch leader
Laura Goepfert	WHOI CTD data analysis
George Knapp	WHOI water sample processor
Toshiko Turner	WHOI water sample processor
Gwyneth Hufford	WHOI CTD watchstander
Francois Primeau	WHOI CTD watchstander
Paul Bennett	WHOI CTD watchstander
George Bouchard	WHOI CTD watchstander
Thomas Jason McKay	WHOI CTD watchstander
Joseph Jennings	OSU nutrient analysis
Calvin Mordy	PMEL nutrient analysis
Guy Mathieu	LDEO CFC analysis
Sally Mathieu	LDEO CFC analysis
Kirk Hargreaves	PMEL CFC analysis
Ken Johnson	BNL CO_2 analysis
Charlotte Haynes	BNL CO_2 analysis
Elizabeth Haynes	BNL CO_2 analysis
Brian Wysor	BNL CO_2 analysis
Melinda Brockington	U. Wash. Dissolved Inorganic Carbon
Gerhard Boenisch	LDEO Helium
Andrea Ludin	LDEO Helium
Cynthia Tynan	NOAA cetacean survey leader
Robert Pitman	NOAA cetacean observer
Richard Rowlett	NOAA cetacean observer
James Cotton	NOAA cetacean observer

THE FRONTS AND CIRCULATION OF THE *SOUTHERN* INDIAN OCEAN

The circulation of the Southern Ocean is dominated by the largest current in the world, the eastward-flowing Antarctic Circumpolar Current (ACC), which is driven by the powerful westerlies at latitudes of 45°-55°s. Specific water masses shoal southward across the ACC, enabling deep waters originating farther north to enter the subpolar regime (Fig. 1, modified from Knox, 1994). Superimposed on the surface circulation are meridional gradients in temperature and salinity which become pronounced at four fronts: the Subtropical Front (STF), formerly called the Subtropical Convergence; the Subantarctic Front (SAF); the Polar Front, formerly called the Antarctic Convergence; and a newly-defined Southern ACC Front (Orsi et al., 1995). The fronts separate five regions characterized by distinct water mass properties and biogeographical zonations. From north to south these zones are: the Subtropical Zone, Subantarctic Zone, Polar Frontal Zone, Antarctic Zone, and the Continental or Subpolar Zone.

The Subtropical Front is a hydrographic boundary that separates the circulation of the ACC from warmer, saltier subtropical waters. The front has a surface temperature gradient of 4°-5°C and a salinity gradient of .5 x $l0^{-3}$ (Deacon, 1982). The SAF, Polar Front, and Southern ACC Front are all zonal jets of intensified eastward flow and are often associated with a confusion of meanders and eddies. All three fronts of the ACC have large horizontal property gradients; across the SAF and Polar Front, temperatures at 100 m decrease by 3°C (Orsi et al., 1995). The Polar Front marks the northern extent of the northward surface flow of Antarctic Surface Water (MSW), characterized by a subsurface temperature minimum of l^{o}-2°C. High concentrations of iron at the Polar Front contribute to the formation of spring phytoplankton blooms which have an order-of-magnitude greater biomass than adjacent ACC waters. (de Baar et al., 1995). The Polar Front is also the site of formation of Antarctic Intermediate Water (AAIW), a well-mixed water mass which sinks to a depth of 1000 m as it spreads northward (Deacon, 1977).

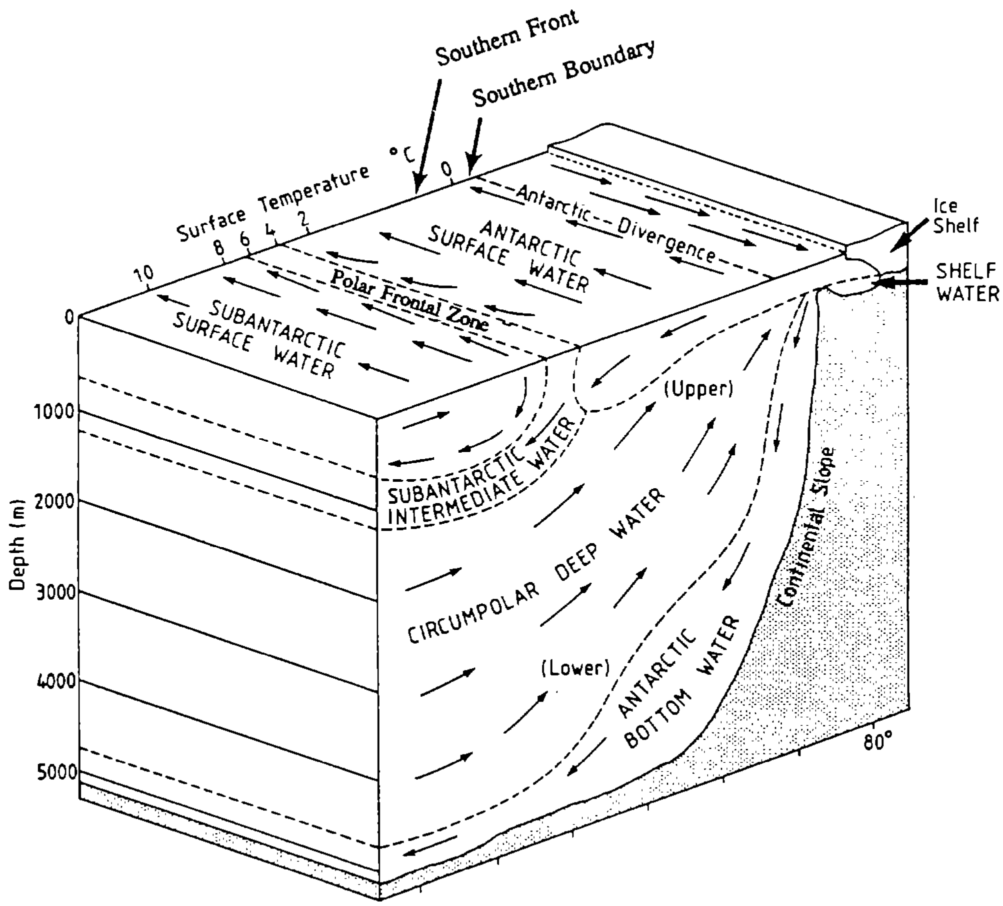

Figure l.--Schematic diagram of the meridional and zonal flow and water masses of the Southern Ocean, modified from Knox (1994), with additional features from Orsi et al. (1995).

Below the AASW and AAIW is a warmer, saline, lower oxygen, and higher nutrient water mass called Circumpolar Deep Water (CDW), which shoals as it moves southward from lower latitudes (Fig. 1). This water mass is separated into Upper CDW (UCDW), defined by low oxygen and high macronutrient concentrations, and Lower CDW (LCDW), characterized by high salinities (Orsi et al., 1995). The poleward edge of the Upper CDW (UCDW) is a watermass boundary which represents the southern boundary of the Antarctic Circumpolar Current; this feature has been named the Southern Boundary of the ACC (Orsi et al., 1995). It is probably this boundary that, in some regions of the Southern Ocean, can be most closely related to the feature formerly known as the Antarctic Divergence (Whitworth, personal communication).

The Antarctic Divergence is the oceanographic regime near the Antarctic continent where the wind reverses direction from the eastward Westerlies, (which drive the ACC), to the westward East Wind Drift. Where the southern water mass boundary of the ACC occurs near the Antarctic Divergence, there is the potential for Ekman upwelling to bring older water, low in oxygen and high in nutrients, closer to the surface. In addition, the Antarctic Divergence in the Indian Ocean is composed of a street of eddies within which Circumpolar Deep water is upwelled to shallower layers (Wakatsuchi and Ohshima, 1994). In the region between 80°-100°E. the trajectories of icebergs have shown this flow reversal and complex circulation at to occur at approximately 63°S (Tehernia and Jeannin, 1980). Moreover, it appears that the boundary region between the east and west winds may be composed of a number of clockwise circulations, rather than continuous East and West Wind Drifts (Deacon, 1984).

The deep circulation of the Southern Indian Ocean is obstructed by the north-south alignment of the Kerguelen Plateau. Deep water flows eastward around the northern edge of the plateau, entering the Australian-Antarctic Basin through the Kerguelen-Amsterdam Passage. As the ACC meets the Kerguelen Plateau, the majority of the current flows around the northern edge of the plateau; however, the path of the southern ACC front is forced south of the plateau (Orsi et al., 1995). A small fraction (approximately 20%; Park et al.,1991) of the ACC progresses southward along the western flank of the plateau and enters a passage, called the Princess Elizabeth Trough, which separates the southern end of the plateau from the Antarctic Continent. In the northern part of this passage, the current flows from west to east (Tohemia and Jeannin, 1983), spawns eddies downstream, and is in general associated with high mesoscale variability. **A** cyclonic eddy has been reported at about 65°S, 80°E (Smith et al., 1984) in the vicinity of the southern-most extent of WOCE leg 18. Nearer the continent, where the wind reverses direction and drives the East Wind Drift, the flow is westward along the shelf and slope.

METHODS

Cruise Track

We departed Fremantle, Australia on December 1, 1994 aboard the Woods Hole Oceanographic Institution's R.V. ***Knorr,*** heading westward approximately along 30°s. Figure 2 presents the cruise track in relation to the Antarctic Continent and the land masses and islands of the Southern Indian Ocean. Figure 3 provides a more detailed map of the locations of conductivity, temperature, and depth (CTD) stations and the sections of the Southern Indian Ocean covered by WOCE hydro legs 18S and 19S. The position of the retreating ice edge is also included in Figure 3. The major bathymetric features of the southeast Indian Ocean are identified in Figure 4 and the mean positions of frontal zones (from Orsi et al., 1995) are included in Figure 5.

At 95°E we turned south and continued along this longitude, crossing the Subantarctic Front (SAF) just north of the crest of the Southeast ***Indian*** Ridge between 42°-45°S (Fig. 4,5). At 45°S we altered course to the southwest heading toward the Kerguelen Plateau. We encountered the Polar Front in the vicinity of 51.8°S, 88.8°E; however, given the complexity of circulation and possible presence of eddies, an approximate position for the front of 52°-53°S is sufficient. We crossed the Kerguelen Plateau and continued as far south along 82°E as the ice would permit (Fig. 3). Line 18S was completed on December 28, 1994, in the Princess Elizabeth Trough with the southern-most extent at CTD station 82: 64.15°S; 81.89°E.

It was originally planned that the ship would head directly east after reaching the ice. However, eastward progress was thwarted by a tongue of ice advecting northward with the western boundary current along the southeastern flank of the Kerguelen Plateau (Fig. 3). The presence of the ice forced the ship to return northward to approximately 60°S before heading east. We again approached the retreating ice-edge along Wilkes Land at 64.83°S, 110.85°E, before commencing the northward, and final, leg of the cruise along 115°E to southwest Australia. After 50 days at sea, ***the*** R. V. ***Knorr*** arrived in Fremantle on January 19, 1995.

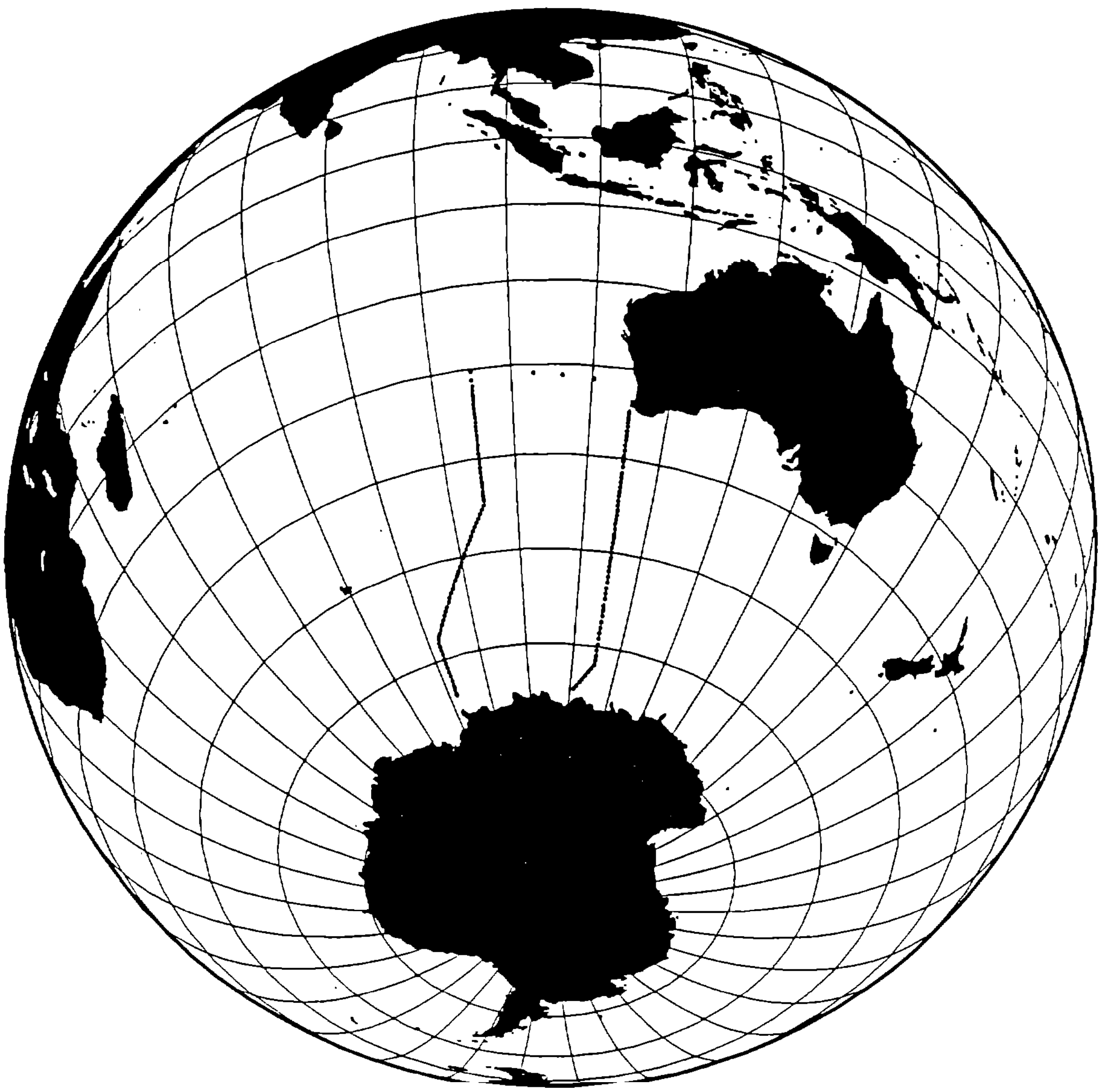

Figure 2.--The cruise track of the R.V. ***Knorr*** in the Southern Indian Ocean from Fremantle, Australia to the ice edge during WOCE I8, I9 from December 1, 1994 - January 19, 1995. The cruise track is composed of the positions of CTD stations conducted during the two meridional hydrolegs.

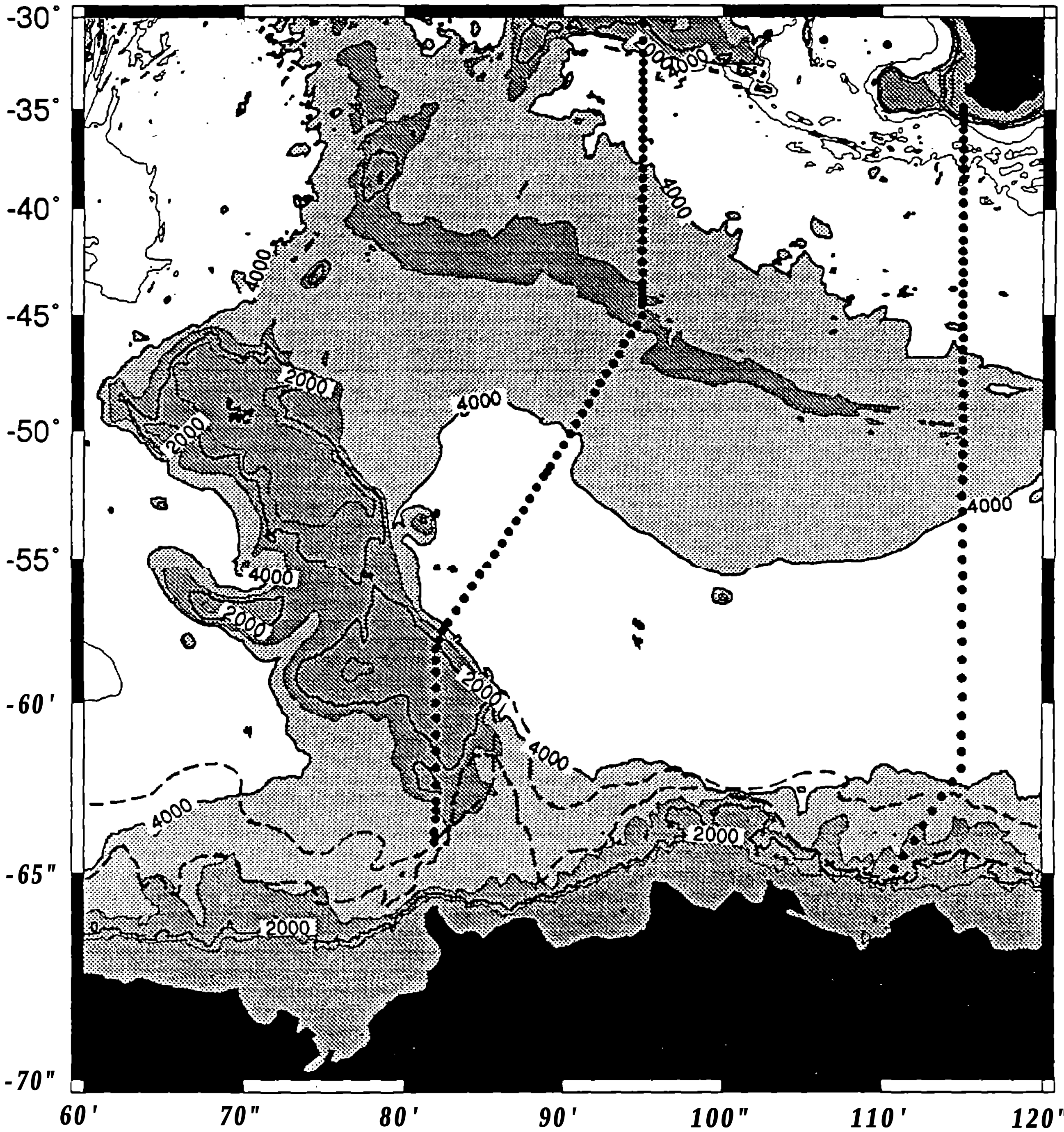

Figure 3.--Location of CTD stations (*) between Fremantle, Australia and the ice edge during WOCE I8, I9 in the Southern *Indian* Ocean from December 1, 1994 - January 19, 1995. The two dashed lines (- -) represent the northern extent of the retreating ice edge on December 1 (the northern line) and December 29, 1994. The advected tongue of ice which extends northward on the eastern flank of the Kerguelen Plateau is apparent.

Survey Methods

Line transect surveys of cetaceans were conducted from the flying bridge of the R. V. ***Knorr*** using 2 pairs of 25x binoculars ("Big-Eyes"). The cradles for the binoculars were mounted on steel stanchions, which in tum were welded to steel bases and chained to the rails for added stability. The final height of the Big-Eye binoculars above the water was 16.08 m. Two observers surveyed from the starboard and port Big-Eye binoculars, while a third centrally positioned observer surveyed the track line with hand-held binoculars. A fourth observer was responsible for all bird sightings within a 300 m radius (180°) of the ship. Sightings were entered into the computer by the author, who typically served as the third or fourth observer. During the two designated CID legs (I8S, I9S), surveys were restricted to the 3-4 hours of steaming between stations. However, during the connecting transits at 30°s and 60°S, when no CTD stations were conducted, cetacean surveys were continued throughout the day as light and weather permitted.

Due to the lack of any weather protection on the flying bridge, it was necessary to construct a wind screen from 9 mm plywood around the periphery of the deck to minimize the wind vibration on the Big-Eyes and the exposure experienced by observers, This arrangement worked extremely well and permitted observations to continue in all but the most inclement weather. The power supply to the flying bridge was suitable for running a portable computer for data entry during the surveys.

Cetaceans were identified to species where possible; however, the cruise was not a designated marine mammal survey and the track line was never broken to obtain a species identification. Therefore the sighting categories of ***Balaenoptera*** spp., unidentified rorqual, or large whale were unavoidable. Nevertheless, several opportunities were provided for observers to photograph humpback ***(Megaptera novueangliae)*** flukes or to document a rare sighting, such as right whales ***(Eubuluena austrulis).***

Sightings obtained during line transects were defined as "on-effort" if the following survey conditions were met: seastate of Beaufort 6 or less; at least one pair of Big-Eye binoculars in use; and a minimum 2-3 nm visibility, Figure 4 illustrates the wide coverage of sighting effort that met these criteria, and identifies three regions where adverse weather prevented observations: 1) the southward leg from 51°-54°S. where severe weather resulted in poor coverage of the Polar Front; 2) the northward leg along 115°E between 53°-57°S, where fog and high winds were encountered; 3) the southeastward approach to the ice between 105°-111°E, across Petersen Bank, where fog and snow hindered observations. Only once, during a Beaufort 10 seastate, were conditions so severe that the ship battened down and hove-to at 53.08°S. 87.69°E.

To obtain the geographic positions of sightings, the GMT time of a sighting was recorded in the computer and later post-processed with 5-minute Global Positioning System (GPS) data provided by Eric Firing, University of Hawaii. Estimates of cetacean densities were determined for the most abundant species, ***Physeter macrocephalus*** and ***Baluenoptera acutorostrata,*** along the southern edge of the Kerguelen Plateau. For all other species and oceanic zones, sightings were too sparse for density estimates. Program “Distance” (Laake et al., 1994) was used to compute density estimates from line transect surveys; this program defines effort as the sum of the transect lengths, in a given region, multiplied by an effective strip width.

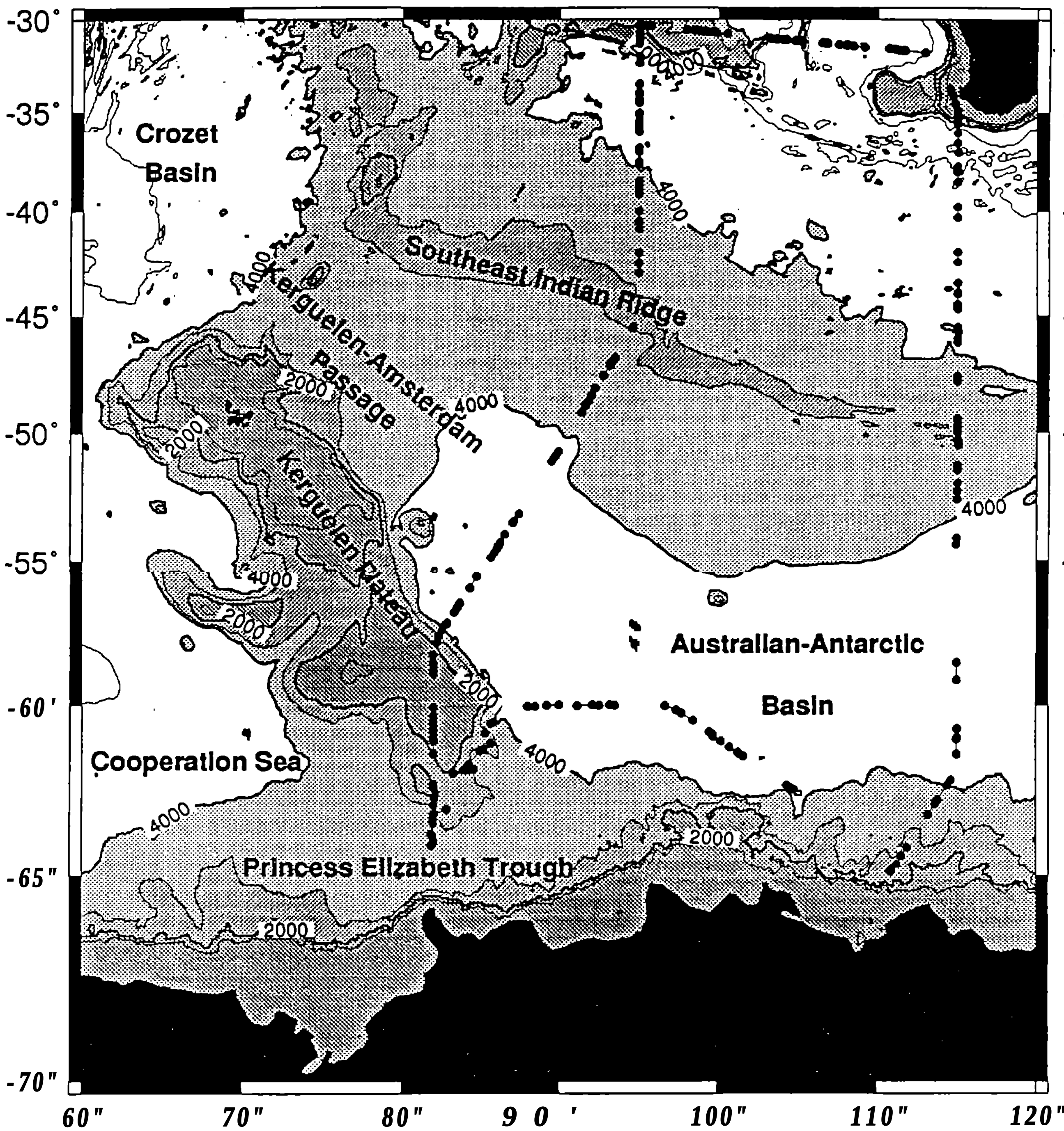

Figure 4.--The distribution of cetacean survey effort during WOCE I8, I9 from December 1, 1994 - January 19, 1995 in the Southern Indian Ocean. Lines connect the positions of the R.V. ***Knorr*** at the beginning and end of each survey period (0).

RESULTS

Distribution of Cetacean Sightings in the Southeastern Indian Ocean

A total of 186 sightings of cetaceans were recorded during the cruise. The highest densities of cetaceans were observed south of 60°S along the southeastern edge of the Kerguelen Plateau, near the mean position of the Southern ACC Front (Fig, 5); there were 92 sightings in this region. Table 2 summarizes the total numbers of sightings for each species. Table 3 identifies the species codes which correspond to the complete listings of sightings in Table 4. Sperm whales (P. ***macrocephalus)*** were the most abundant large cetacean south of the Polar Front. Whales congregated either directly over, or in close proximity to, complex bathymetry, such as the edge topography of the Kerguelen Plateau (Figs. 6 and 7) and the shelf/shope region off southwestern Australia (Fig. 8). The average density of sperm whales at the southeastern edge of the Kerguelen Plateau was 1.3 whales 100 km-^{2}.

Minke whales were the second most abundant species of large cetacean in the Southeastern Indian Ocean. Eighty-five percent of minke whale sightings occurred south of 60°S near the retreating ice edge in the Antarctic and Continental Zones (Fig. 9). Seventy-four percent of sightings were associated with the edge of the Kerguelen Plateau (Fig. 10). The highest density of minke whales was observed along the eastern flank of the plateau (approximately 62°5, 84.5°E), along the tongue of ice advecting northward with the western boundary current. Minke whales were not observed in the deep (> 4000 m) Australian-Antarctic Basin.

Migrating humpbacks ***(M. novaeangliae)*** were presumably from the population which winters along western Australia. Results from whale marking confirm that humpbacks migrate in a southwesterly direction from breeding areas off western Australia to the Antarctic between 75°-115°E (Brown et al., 1974). During the present survey, this species was observed as far south as the retreating ice (64°S). Eighty-seven percent of humpback sightings occurred south of the Polar Front (Fig. 11). and over half of sightings were associated with the Kerguelen Plateau (Fig. 12). The lack of any sightings of humpbacks during the northward leg along 115°E suggests that few whales migrating from western Australia head directly south. Rather,

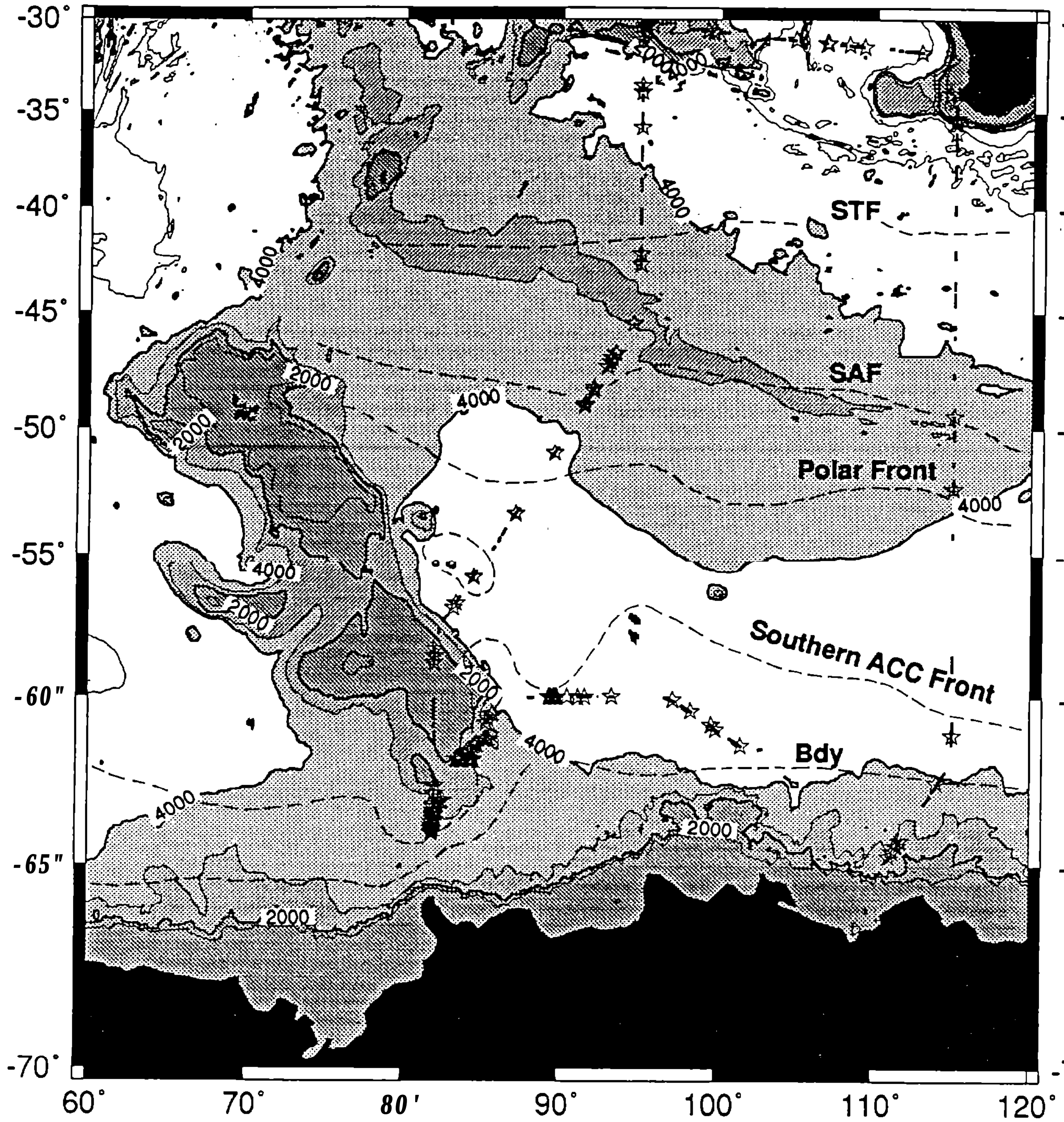

Figure 5.--The distribution of cetacean sightings (*), relative to effort (-), in the Southern Indian Ocean during WOCE I8, I9 from December 1, 1994 - January 19, 1995. The mean positions of the Subtropical Front (STF), the Southern Boundary (Bdy) of the Antarctic Circumpolar Current (ACC), and the three fronts of the ACC (modified from Orsi et al., 1995) are plotted for comparison: the Subantarctic Front (SAF); the Polar Front; and the Southern ACC Front. The dashed circle on the east side of the Kerguelen Plateau (82°E) represents a clockwise eddy generated by the Southern ACC Front. Cetaceans were most abundant off the southeastern edge of the Kerguelen Plateau (82°-86°E); there were 92 sightings in this region.

Table 2.--Cetacean sightings during WOCE I8S, I9S, Southern Indian Ocean. The total number of on-effort sightings and cetaceans is followed by the total numbers from on- and off-effort combined (in parentheses). The average densities for the two most abundant species at the edge of the Kerguelen Plateau (K.P.) are given,

Species	Number of Sightings	Number of Whales	Density (whales 100 km^{-2})
Physeter macrocephalus	50	50	1.3 (K.P.)
Balaenoptera acutorostrata	25 (27)	41 (43)	1.6 (K.P.)
Megaptera novaeangliae	12 (15)	33 (39)	-
Hyperoodon planifrons	18 (21)	31 (34)	-
Orcinus orca	5	44	-
Balaenoptera spp.	5	7	-
unidentified rorqual	11	14	-
"*Like Minke*"	2 (6)	2 (13)	-
Eubalaena australis	1	2	-
Balaenoptera musculus	0 (1)	(1)	-
B. musculus brevicauda	1	1	-
Mesoplodon grayi	1	1	-
Mesoplodon spp.	1	3	-
Berardius arouxii	1	2	-
Ziphiidae	8	12	-
Globicephala melaena	2	205	-
Lagenorhynchus cruciger	2	13	-
Stenella coeruleoalba	1	25	-
unidentified small cetacean	7 (9)	63 (73)	-
unidentified large whale	12	13	-

Table 3.--Cetacean species codes for WOCE I8, I9, Southern Indian Ocean. Descriptions for these codes are necessary to interpret Table 4.

Code	Species	Common name
13	*Stenella coeruleoalba*	Striped Dolphin
27	*Lagenorhynchus cruciger*	Hourglass Dolphin
37	*Orcinus orca*	Killer Whale
38	*Globicephala malaena*	Long-finned Pilot Whale
46	*Physeter macrocephalus*	Sperm Whale
49	family Ziphiidae	Beaked Whales
50	*Hyperoodon planifrons*	S. Bottlenose Whale
51	*Mesoplodon* spp.	
55	*Berardius arnouxii*	Arnoux's Beaked Whale
58	*Mesoplodon grayi*	Gray's Beaked Whale
70	*Balaenoptera* spp.	
71	*Balaenoptera acutorostrata*	Minke Whale
74	*Balaenoptera musculus brevicauda*	Pygmy Blue Whale
75	*Balaenoptera musculus*	Blue Whale
76	*Megaptera novaeangliae*	Humpback Whale
77		unidentified dolphin or porpoise
78		unidentified small cetacean (< ~ 30 ft)
79		unidentified large cetacean (> ~ 30 ft)
80	*Eubalaena australis*	Southern Right Whale
93		Blue or Fin Whale
94		Fin or Sei Whale
95		unidentified rorqual
96		unidentified cetacean (no size estimate)
97		like Minke Whale

Table 4.--Cetacean sightings during WOCE I8, I9 Dec. 1, 1994 - Jan. 19, 1995. The form of the observation effort (E) during each sighting is listed in the first column: on-effort sighting using Big-Eye binoculars (1) or hand-held binoculars (2); off-effort sighting (3); sighting which is possibly the same as the previous one (4). The number of the sighting (No.) and the species code (as described in Table 3) are listed. The year day assumes a starting value of 0 for January 1. Other variables include: Greenwich Mean Time (GMT); Beaufort sea state (B); ship course (C) (°); ship speed (V) (kts); sighting bearing (S)(°); reticle measure (R) on the Big-Eye binoculars; calculated radial distance (D_r) (km) from the ship to the whale, and the perpendicular distance (D_p) (km) from the whale to the track line; the best estimate of the number of whales (N) observed; and the highest (N_h) and lowest (N_l) estimate of group size. Missing data is flagged with a dash (-).

E	No.	Species code	Year day	GMT	Latitude °S	Longitude °E	B	C	V	S	R	D_r	D_p	N	N_h	N_l
1	1	77	334	223807	-31.742808	112.734158	3	275	11.2	53	0.5	6.789	5.421	20	40	15
4	2	77	334	224230	-31.741377	112.719013	3	275	11.2	-	-	-	-	-	-	-
1	3	77	335	224850	-31.455643	109.079525	5	275	10.5	30	11.0	0.970	0.485	1	1	1
1	4	77	336	033421	-31.359092	108.088092	4	275	10.0	90	6.5	1.511	1.51	6	10	5
1	5	95	336	095426	-31.264853	106.760418	3	275	10.5	87	0.4	7.323	7.313	1	1	1
1	6	71	336	102447	-31.256637	106.654138	3	275	10.5	50	0.3	7.990	6.120	1	1	1
1	7	49	337	003711	-31.100707	104.698247	3	275	10.5	13	1.3	4.469	1.005	1	1	1
1	8	71	338	045735	-30.648180	99.478272	3	275	10.5	350	0.2	8.873	1.540	1	1	1
1	9	51	338	063503	-30.635278	99.132167	2	275	10.5	327	3.0	2.696	1.468	3	4	3
1	10	78	338	225403	-30.347982	95.640485	3	275	10.5	40	0.8	5.639	3.624	3	-	-
1	11	77	339	005158	-30.317400	95.240170	4	275	10.5	0	0.8	5.639	0.000	12	15	10
1	12	13	339	012734	-30.309698	95.115312	4	275	10.5	339	0.8	5.639	2.020	25	30	20
2	13	71	339	085406	-30.868870	95.000053	4	180	9.5	340	-	0.5	0.2	2	3	2
1	14	50	339	102748	-31.102940	94.997272	4	180	8.0	16	0.7	5.966	1.644	2	2	2
1	15	74	341	025639	-33.599273	95.009210	3	180	9.0	359	0.8	5.639	0.098	1	1	1
1	16	70	341	051942	-33.947508	95.010582	4	180	9.0	320	0.5	6.789	4.363	2	3	2
1	17	49	342	083845	-35.829450	95.002442	4	180	9.0	9	5.0	1.859	0.291	1	1	1
1	18	49	346	015250	-42.259908	95.011382	5	180	10.0	354	2.5	3.044	0.318	1	1	1
1	19	58	346	070508	-42.766735	95.011070	5	180	10.5	305	3.5	2.422	1.983	1	2	1
2	20	38	348	005850	-45.488187	94.603755	5	212	7.0	315	-	0.9	0.7	80	150	60
2	21	94	349	0000--	-46.803420	93.480460	6	-	-	90	-	0.9	0.7	1	1	1
2	22	94	349	001313	-46.821357	93.456657	6	220	8.2	-	-	1.9	-	2	2	2
2	23	70	349	021109	-47.013443	93.248922	6	220	8.2	-	-	0.9	-	1	1	1
1	24	76	349	084705	-47.191050	93.119080	5	215	8.8	20	-	-	-	2	2	2
1	25	97	349	101610	-47.387622	92.931418	5	215	8.8	39	8.0	1.274	0.801	1	1	1
3	26	95	349	1135--	-47.567467	92.762867	5	-	0.0	-	-	-	-	1	1	1
1	27	77	349	233935	-48.286390	92.109335	5	208	10.2	293	0.4	7.323	6.741	-	-	20
2	28	95	350	002047	-48.389490	92.027917	6	208	10.2	345	-	2.8	0.7	1	1	1
1	29	95	350	104228	-48.967053	91.535405	6	214	9.5	335	0.4	7.323	3.094	1	1	1
1	30	95	350	111222	-49.030620	91.468640	7	214	9.5	324	1.2	4.657	2.737	2	2	1
3	31	95	351	1000--	-50.531313	90.037885	8	210	9.5	-	-	-	-	1	1	1
1	32	38	352	030621	-50.979795	89.606913	5	220	6.6	295	4.0	2.199	1.993	125	150	100
1	32	27	352	030621	-50.979795	89.606913	5	220	6.6	295	4.0	2.199	1.993	10	12	8
1	33	76	352	063615	-50.998270	89.587232	5	220	8.0	295	0.8	5.639	5.110	2	2	2
3	34	27	353	125538	-52.670733	87.874460	5	-	0.0	-	-	0.25	-	3	4	2
1	35	49	354	115348	-53.377062	87.168375	4	209	6.7	9	1.0	5.094	0.797	3	4	2
1	36	96	354	120541	-53.400337	87.140850	4	209	6.7	310	2.0	3.502	2.683	1	1	1
1	37	50	356	052810	-55.867762	84.493458	4	222	10.0	355	0.8	5.639	0.491	2	3	2
1	38	50	356	054055	-55.896862	84.455662	4	222	10.0	55	3.5	2.422	1.983	1	1	1
1	39	49	357	003529	-56.850470	83.360967	6	215	9.5	55	0.8	5.639	4.618	1	1	1
2	40	76	357	053149	-57.001212	83.202460	7	218	10.0	50	-	3.7	2.8	3	4	3
3	41	76	357	1020--	-57.316152	82.766570	6	-	0.0	-	-	0.4	-	3	3	3
3	42	97	357	1430--	-57.512510	82.534385	-	-	0.0	-	-	5.6	-	5	5	4
3	43	97	357	1500--	-57.511305	82.528882	-	-	0.0	-	-	6.5	-	2	2	2
3	44	97	357	2140--	-57.607760	82.339570	-	-	0.0	-	-	2.8	-	2	2	2
3	45	97	357	2214--	-57.675002	82.326147	-	-	0.0	-	-	1.9	-	2	3	2
3	46	76	358	0515--	-58.224242	81.995238	3	-	0.0	-	-	0.1	-	4	4	4
1	47	95	358	075028	-58.456025	82.001518	3	183	11.0	344	0.4	7.323	2.018	1	2	1
1	48	95	358	110016	-58.678470	81.997765	3	180	9.0	47	0.3	7.990	5.843	3	4	3

Table 4.—Continued.

E	No.	Species code	Year day	GMT	Latitude °S	Longitude °E	B	C	V	S	R	D_r	D_p	N	N_h	N_l
1	49	76	358	110120	-58.681610	81.997742	3	180	9.0	352	0.5	6.789	0.945	3	3	3
1	50	71	358	121202	-58.897858	81.999520	2	180	9.0	340	1.2	4.657	1.593	1	2	1
1	51	51	360	021839	-62.717925	82.047945	2	180	6.0	120	0.5	6.789	5.881	2	2	2
1	52	37	360	034454	-62.968163	81.999767	2	188	13.0	346	0.4	7.323	1.771	20	25	18
1	53	95	360	090535	-63.451473	81.993158	2	180	12.5	355	0.1	10.191	0.888	1	-	-
2	54	71	360	091105	-63.470953	81.992985	2	180	12.5	12	-	2.8	0.6	2	2	1
1	55	46	360	091218	-63.475703	81.993028	2	180	12.5	323	0.8	5.639	3.393	1	1	1
1	56	79	360	091342	-63.480422	81.993067	2	180	12.5	294	0.0	14.246	13.013	1	-	-
1	57	46	360	123827	-63.528958	82.008102	2	180	-	13	0.5	6.789	1.527	1	1	1
1	58	46	360	124229	-63.540527	82.018743	2	180	-	52	0.1	10.191	8.029	1	1	1
1	59	95	360	124713	-63.556332	82.031843	2	180	-	72	0.0	14.246	13.547	1	-	-
1	60	95	360	124809	-63.559748	82.034598	2	180	-	81	0.0	14.246	14.070	1	-	-
1	61	46	360	124838	-63.561427	82.035978	2	180	-	75	0.8	5.639	5.446	1	1	1
1	62	46	360	125500	-63.582617	82.054318	2	180	-	85	0.2	8.873	8.839	3	4	3
1	63	46	360	125501	-63.582617	82.054318	2	180	-	89	0.8	5.639	5.638	1	1	1
2	64	95	360	130240	-63.608712	82.069762	2	180	-	85	-	-	-	1	1	1
1	65	46	360	130309	-63.610473	82.070067	2	180	-	85	0.3	7.990	7.959	1	1	1
1	66	46	360	133339	-63.716970	82.063435	0	180	13.0	291	0.2	8.873	8.283	2	3	2
1	67	46	360	134337	-63.751103	82.053430	0	180	13.0	302	0.3	7.990	6.775	1	1	1
1	68	46	360	140042	-63.802647	81.997352	0	229	13.0	353	0.1	10.191	1.242	1	1	1
1	69	71	360	142559	-63.875750	81.885300	0	218	13.0	303	0.4	7.323	6.141	1	1	1
1	70	76	360	143114	-63.890983	81.862757	0	150	13.0	358	0.4	7.323	0.256	2	3	2
1	71	46	360	144123	-63.920302	81.903322	0	150	13.0	64	5.0	1.859	1.671	1	1	1
1	72	76	360	150056	-63.979425	81.976278	0	155	13.0	280	6.0	1.611	1.587	2	2	2
3	73	71	360	-	-64.149122	81.892103	-	-	-	-	-	0.0	-	1	-	-
1	74	71	361	015559	-64.112757	81.870178	0	0	12.5	8	1.7	3.856	0.537	1	1	1
1	75	71	361	015927	-64.100915	81.871690	0	0	12.5	358	3.3	2.524	0.088	3	3	3
1	76	46	361	020832	-64.068145	81.875450	0	0	12.5	349	0.1	10.191	1.944	1	2	1
1	77	71	361	021036	-64.061042	81.876750	0	0	12.5	4	1.6	3.991	0.278	2	3	2
1	78	46	361	021512	-64.044555	81.882227	0	0	12.5	310	0.1	10.191	7.806	1	1	1
1	79	71	361	021525	-64.043963	81.882427	0	0	12.5	353	0.5	6.789	0.827	1	1	1
1	80	46	361	022929	-63.994165	81.898577	1	0	12.5	287	0.4	7.323	7.003	1	1	1
1	81	46	361	023009	-63.991808	81.899365	1	0	12.5	17	0.3	7.990	2.336	1	1	1
1	82	46	361	024252	-63.947085	81.909658	1	0	12.5	332	0.6	6.345	2.978	1	1	1
1	83	96	361	024438	-63.940508	81.911502	1	0	12.5	25	0.5	6.789	2.869	1	1	1
1	84	71	361	071333	-63.801120	81.860580	2	11	10.7	330	5.5	1.726	0.863	1	1	1
1	85	46	361	072334	-63.770632	81.869632	2	11	10.7	314	0.6	6.345	4.563	1	1	1
1	86	71	361	074630	-63.700323	81.891227	2	11	10.7	327	0.5	6.789	3.697	3	4	3
1	87	46	361	075418	-63.676497	81.902468	2	70	10.7	357	0.2	8.873	0.464	1	1	1
1	88	46	361	081501	-63.611458	81.927007	1	70	10.7	36	1.4	4.296	2.525	1	1	1
1	89	46	361	081909	-63.598302	81.931297	1	70	10.7	30	2.5	3.044	1.522	1	1	1
1	90	46	361	093429	-63.363463	81.987423	2	4	11.5	356	0.7	5.966	0.416	1	1	1
1	91	46	361	094228	-63.338740	81.989545	3	4	11.5	351	0.2	8.873	1.388	1	1	1
1	92	46	361	100156	-63.278608	81.996697	3	4	11.5	350	2.8	2.825	0.490	1	1	1
1	93	46	361	135159	-63.202300	82.376900	3	70	11.5	325	0.5	6.789	3.893	1	1	1
1	94	78	361	135301	-63.201195	82.383450	3	70	11.5	322	0.6	6.345	3.905	1	1	1
1	95	46	361	141850	-63.173365	82.550457	3	70	11.5	4	0.3	7.990	0.557	1	2	1
1	96	79	361	142333	-63.168040	82.581612	3	70	11.5	44	0.2	8.873	6.163	1	1	1
1	97	79	361	223950	-61.955457	83.389933	3	52	10.8	40	2.5	3.044	1.957	2	3	2
1	98	46	361	224129	-61.952898	83.399470	3	52	10.8	293	6.5	1.511	1.391	1	1	1
1	99	46	361	224550	-61.950747	83.427628	3	90	10.8	350	0.1	10.191	1.769	1	1	1
1	100	46	361	224644	-61.950800	83.433302	3	90	10.8	356	0.2	8.873	0.619	1	1	1
1	101	46	361	224703	-61.950730	83.435462	3	90	10.8	358	0.5	6.789	0.237	1	1	1
1	102	46	361	224942	-61.950868	83.453312	3	90	10.8	60	4.0	2.199	1.904	2	2	1
1	103	46	361	225700	-61.952815	83.502267	3	90	10.8	345	0.6	6.345	1.642	2	2	1
1	104	46	361	230504	-61.954487	83.555662	3	90	10.8	301	0.4	7.323	6.277	1	1	1
1	105	46	361	230633	-61.954815	83.565677	3	90	10.8	358	0.1	10.191	0.356	1	1	1

Table 4.-Continued.

E	No.	Species code	Year day	GMT	Latitude °S	Longitude °E	B	C	V	S	R	D_r	D_p	N	N_k	N_l
1	106	93	361	230901	-61.955327	83.582323	3	90	10.8	330	0.0	14.246	7.122	1	1	1
1	107	46	361	232110	-61.957868	83.663453	3	90	10.8	278	3.0	2.696	2.670	1	1	1
1	108	46	361	233258	-61.957858	83.742398	3	90	10.8	45	0.1	10.191	7.205	1	1	1
1	109	46	361	233710	-61.960930	83.770555	3	90	10.8	325	1.2	4.657	2.671	1	1	1
1	110	46	361	234824	-61.962993	83.845232	3	90	10.8	44	7.0	1.423	0.988	1	1	1
1	111	46	361	235822	-61.964623	83.900320	3	90	10.8	356	0.2	8.873	0.619	1	1	1
1	112	46	362	004527	-61.971353	84.215327	3	90	10.8	310	8.0	1.274	0.976	1	1	1
1	113	46	362	004817	-61.969040	84.233788	3	90	10.8	345	1.0	5.094	1.318	1	1	1
1	114	71	362	011314	-61.958827	84.365022	2	83	8.0	34	1.5	4.138	2.313	7	10	6
2	115	71	362	011537	-61.958422	84.375900	2	83	8.0	40	-	18.5	11.9	1	1	1
1	116	71	362	012447	-61.959895	84.413288	2	144	8.0	25	0.8	5.639	2.383	2	2	1
1	117	71	362	013450	-61.964738	84.445062	2	90	8.0	21	2.3	3.212	1.151	2	2	2
2	118	71	362	014204	-61.961607	84.477092	2	75	8.0	353	-	2.2	0.3	1	1	1
2	119	71	362	015228	-61.951792	84.528270	2	70	11.5	330	-	1.9	0.9	1	1	1
1	120	46	362	042741	-61.767640	84.270400	2	34	10.5	340	2.5	3.044	1.041	1	1	1
1	121	46	362	043207	-61.755533	84.287393	2	34	10.5	358	0.0	14.246	0.497	1	2	1
1	122	71	362	043543	-61.745593	84.301095	2	34	10.5	355	10.0	1.054	0.092	2	2	1
1	123	46	362	045537	-61.694563	84.382588	2	38	10.5	330	1.0	5.094	2.547	1	1	1
2	124	97	362	045934	-61.684208	84.399093	2	38	10.5	37	-	0.6	0.3	1	1	1
1	125	71	362	051600	-61.640562	84.468477	2	22	10.5	16	0.4	7.323	2.018	1	1	1
1	126	71	362	051742	-61.635992	84.468477	2	22	10.5	20	0.2	8.873	3.034	1	1	1
1	127	46	362	055121	-61.551838	84.614515	2	43	10.5	29	2.5	3.044	1.476	1	1	1
1	128	71	362	060833	-61.510040	84.697045	2	43	10.5	40	14.0	0.784	0.504	1	1	1
1	129	37	362	060953	-61.507063	84.703892	2	43	10.5	1	0.8	5.639	0.098	9	12	8
1	130	50	362	061936	-61.486778	84.755985	2	43	10.5	352	7.0	1.423	0.198	1	1	1
1	131	76	362	074027	-61.343018	85.203470	1	90	11.6	314	0.3	7.990	5.747	3	4	3
1	132	76	362	074657	-61.339870	85.247080	1	85	11.6	342	2.0	3.502	1.082	2	2	2
1	133	46	362	080412	-61.331393	85.363510	1	85	11.6	51	0.1	10.191	7.919	1	1	1
1	134	46	362	080521	-61.331032	85.371540	1	85	11.6	314	0.2	8.873	6.382	1	1	1
1	135	79	362	081046	-61.328308	85.408910	1	85	11.6	19	0.3	7.990	2.601	1	1	1
1	136	37	362	081953	-61.324670	85.470575	1	85	11.6	69	0.4	7.323	6.836	-	-	1
1	136	76	362	081953	-61.324670	85.470575	1	85	11.6	69	0.4	7.323	6.836	3	3	3
1	137	50	362	083335	-61.200853	85.638242	1	85	11.6	31	0.2	8.873	4.569	2	2	2
1	138	71	362	091944	-61.200853	85.638242	0	0	11.6	35	1.0	5.094	2.921	1	1	1
1	139	50	362	114248	-60.825425	85.305415	1	0	12.0	347	3.5	2.422	0.545	1	1	1
1	140	37	362	123031	-60.682867	85.431750	1	24	12.0	0	0.6	6.345	0.000	6	10	6
1	141	50	362	134611	-60.544898	85.710718	1	51	11.0	2	0.8	5.639	0.197	4	4	3
1	142	79	362	135008	-60.537012	85.731725	1	51	11.0	7	0.0	14.246	1.736	1	1	1
1	143	79	363	014829	-59.994127	89.302560	3	86	11.5	61	0.3	7.990	6.987	3	4	2
1	144	51	363	015501	-59.993645	89.338408	3	86	11.5	58	1.6	3.991	3.384	1	1	1
1	145	50	363	021104	-59.992038	89.440645	3	86	11.5	24	0.6	6.345	2.580	3	4	2
1	146	79	363	023450	-59.989643	89.589718	3	88	11.5	27	0.1	10.191	4.626	3	3	2
1	147	79	363	024655	-59.988172	89.666760	3	88	11.5	50	1.0	5.094	3.902	2	2	2
1	148	79	363	025821	-59.987063	89.738670	3	88	11.5	12	1.0	5.094	1.059	1	1	1
1	149	50	363	030504	-59.986365	89.781332	3	88	11.5	62	2.7	2.894	2.555	1	1	1
1	150	50	363	031524	-59.985332	89.847547	3	88	11.5	24	3.0	2.696	1.096	2	2	2
3	151	76	363	0450--	-59.987498	90.463337	3	-	-	20	4.0	2.199	0.752	2	2	2
1	152	97	363	063803	-60.006222	91.164668	3	90	11.7	0	0.6	6.345	0.000	1	1	1
1	153	76	363	074428	-59.998030	91.584095	3	87	11.7	3	0.1	10.191	0.533	4	5	4
1	154	50	363	122722	-59.976785	93.331707	4	92	11.6	311	2.0	3.502	2.643	1	1	1
1	155	50	363	233116	-60.080268	97.229588	3	124	12.8	320	0.4	7.323	4.707	2	2	2
1	156	50	364	024425	-60.442187	98.355882	3	124	12.8	5	0.8	5.639	0.491	6	8	5
3	157	75	364	0325--	-60.811202	99.463855	3	-	-	63	4.0	2.199	1.959	1	1	1
1	158	80	364	062757	-60.871943	99.653527	3	124	12.8	353	0.4	7.323	0.892	2	2	2
1	159	50	364	081808	-61.024293	99.932882	3	124	12.8	303	1.3	4.469	3.747	1	1	1
3	160	76	364	1005--	-61.229260	100.588038	-	-	-	-	-	-	-	1	1	1
3	160	50	364	-	-	-	-	-	-	-	-	-	-	1	1	1

Table 4.—Continued.

E	No.	Species code	Year day	GMT	Latitude °S	Longitude °E	B	C	V	S	R	D_r	D_p	N	N_h	N_l
1	161	49	364	123647	-61.520853	101.522452	1	124	12.8	320	0.4	7.323	4.707	3	4	3
3	162	50	364	130427	-61.575860	101.689020	1	-	-	-	-	-	-	1	1	1
3	163	76	364	2110--	-62.348732	104.098338	4	-	-	-	-	-	1	3	3	3
3	164	50	0	031036	-63.022653	106.364593	4	124	12.5	355	-	0.9	0.1	1	1	1
3	165	50	0	035614	-63.105482	106.616885	4	124	10.2	315	-	0.2	0.1	1	1	1
2	166	71	1	061300	-64.736650	110.999772	4	40	11.5	0	-	0.2	0.0	1	1	1
1	167	55	1	070448	-64.598563	111.229490	5	40	11.5	13	2.0	3.502	0.788	2	3	1
1	168	71	1	070648	-64.593358	111.238448	5	40	11.5	21	2.5	3.044	1.091	1	1	1
1	169	50	1	080454	-64.443928	111.502142	5	40	11.5	355	2.0	3.502	0.305	2	3	2
1	170	49	1	081139	-64.425967	111.531720	5	40	11.5	336	2.0	3.502	1.424	1	1	1
1	171	50	1	085743	-64.304688	111.731847	6	40	11.5	310	2.5	3.044	2.332	2	2	2
3	172	71	1	1015--	-64.106568	112.065103	6	-	0.0	-	-	-	-	1	1	1
1	173	50	2	071057	-62.634573	114.006553	4	20	11.8	349	9.0	1.153	0.220	1	1	1
1	174	96	3	030519	-61.202367	114.994885	5	0	10.0	84	0.5	6.789	6.751	1	1	1
1	175	49	7	225524	-52.424583	114.997162	7	0	9.7	29	2.0	3.502	1.698	1	1	1
3	176	77	9	0700--	-49.726965	115.004773	6	354	10.0	-	-	-	-	2	-	-
1	177	50	9	114744	-49.481990	114.988755	5	357	10.0	31	6.0	1.611	0.830	1	1	1
3	178	77	11	0245--	-46.203782	115.009268	6	357	10.5	-	-	-	-	8	-	-
1	179	37	16	073419	-36.052132	115.003073	4	357	13.4	37	1.4	4.296	2.585	8	12	6
1	180	46	16	230655	-35.439555	114.999898	4	1	12.5	60	0.4	7.323	6.342	4	5	4
1	181	46	16	230921	-35.431425	114.999945	4	1	12.5	44	0.3	7.990	5.549	1	1	1
1	182	77	16	235053	-35.284308	115.000738	4	1	12.5	344	0.5	6.789	1.871	7	10	4
1	183	46	17	000533	-35.231358	115.002588	4	1	12.5	291	0.2	8.873	8.283	2	3	2
1	184	46	17	000639	-35.227808	115.002792	4	1	12.5	301	0.2	8.873	7.605	1	1	1
1	185	77	17	073208	-34.390767	114.812105	5	340	12.5	319	4.0	2.199	1.442	12	25	10
1	186	78	17	094155	-33.940393	114.615580	6	340	13.4	13	0.2	8.873	1.996	3	4	2

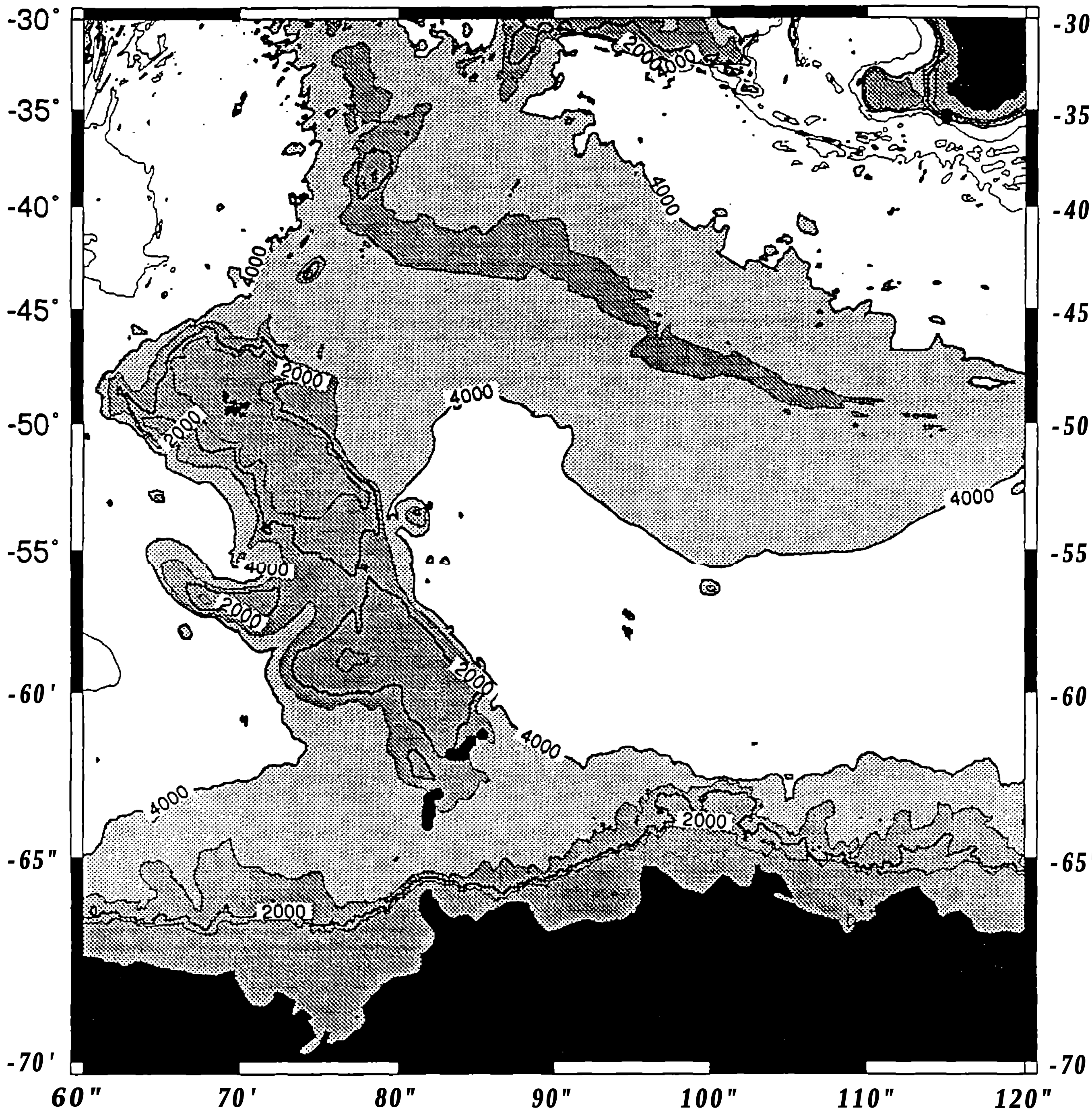

Figure 6.--The distribution of sperm whale (Physeter macrocephalus) sightings (0) in the Southern Indian Ocean during WOCE I8, I9 from December 1, 1994 - January 19, 1995. Sperm whales were observed along complex topography of the southeast corner of the Kerguelen Plateau and the shelf break off southwestern Australia.

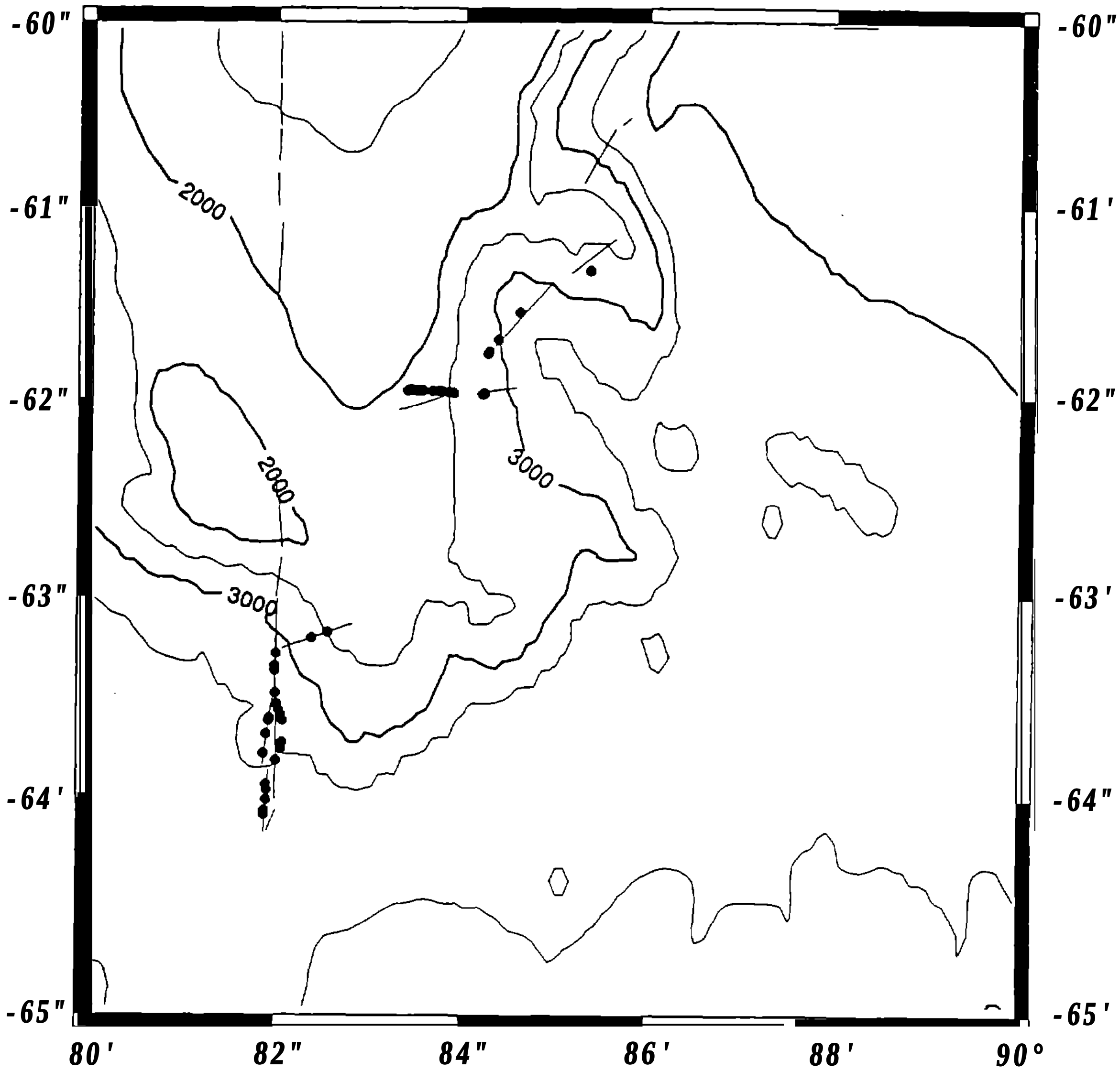

Figure 7.--The distribution of sperm whale ***(Physeter macrocephalus)*** sightings (0) on December 26-28, 1994 along the southeast comer of the Kerguelen Plateau and northern Princess Elizabeth Trough. Sperm whales were observed as far south as the ice edge and were associated with complex topography between 2000 - 4000 m depth. Continuous survey effort is represented by straight lines, connecting the position of the R.V. Knorr at the beginning and end of the survey periods. The variable orientation of the cruise track during the northward transit between 64°S and 60°S reflects the difficult navigation along a tongue of ice.

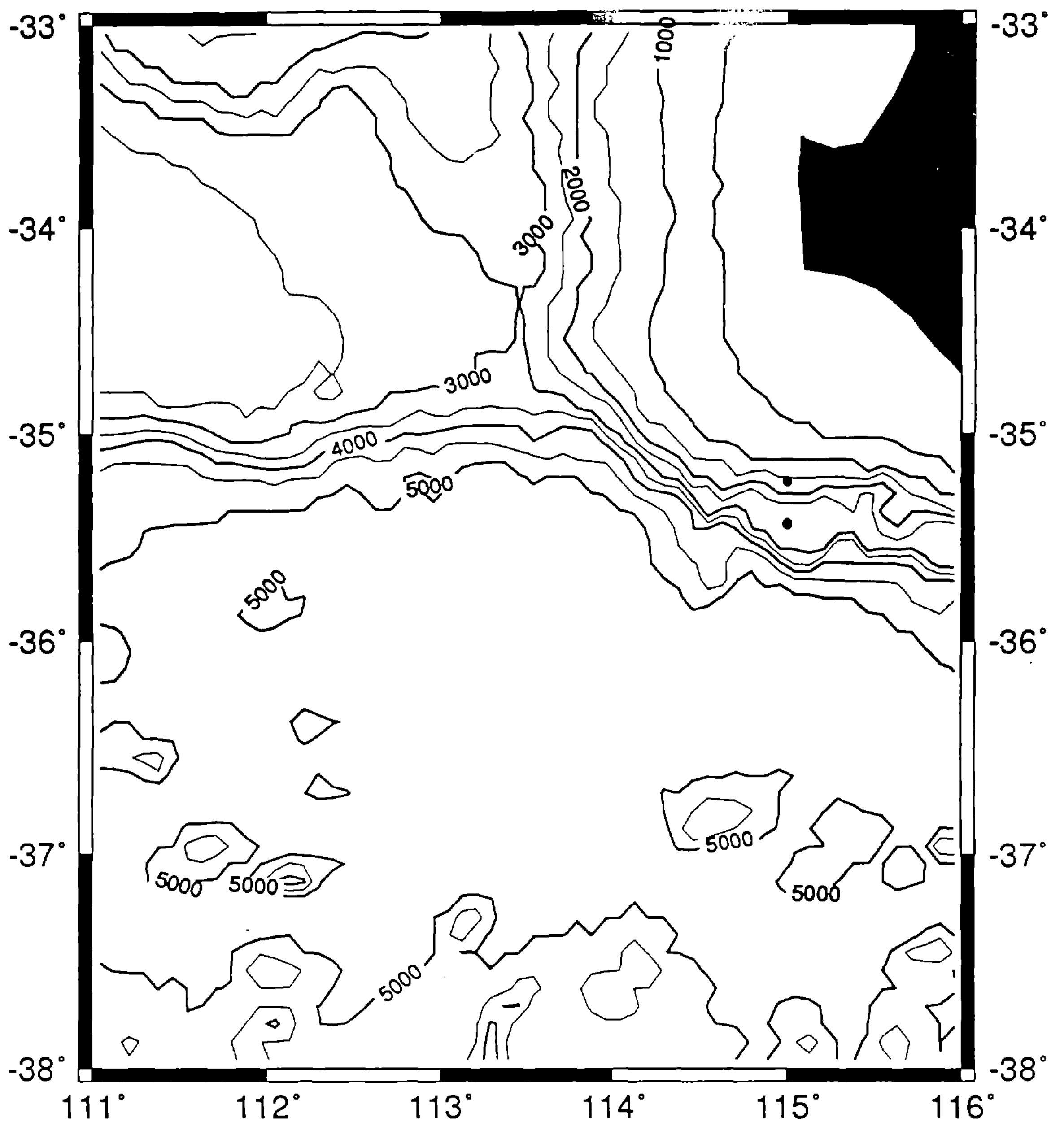

Figure 8.--The distribution of sperm whale ***(Physeter mucrocephulus)*** sightings (0) during January 16 - 17, 1995, along the complex shelf edge topography of southwestern Australia. Each symbol (a) represents two closely spaced sightings along 115°E during WOCE leg I9.

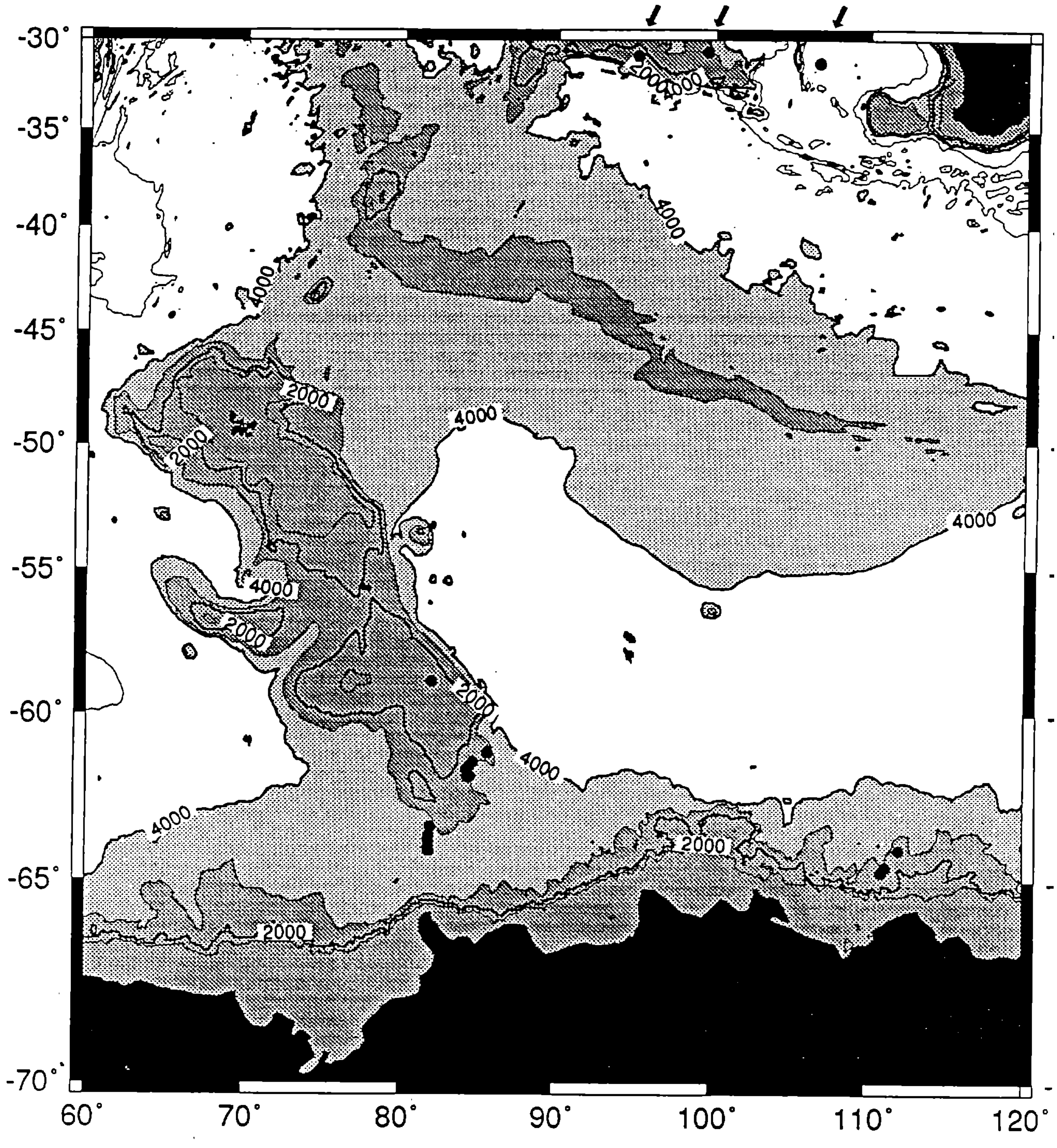

Figure 9.--The distribution of minke whale ***(Balaenoprera acutorostrata)*** sightings (0) in the Southern Indian Ocean during WOCE I8, I9 from December 1, 1994 - January 19, 1995. Minke whale-s were observed throughout the full latitudinal range of the cruise (approximately 31° - 64°S); however, 74% of sightings were associated with the southern edge of the Keguelen Plateau along the retreating ice.

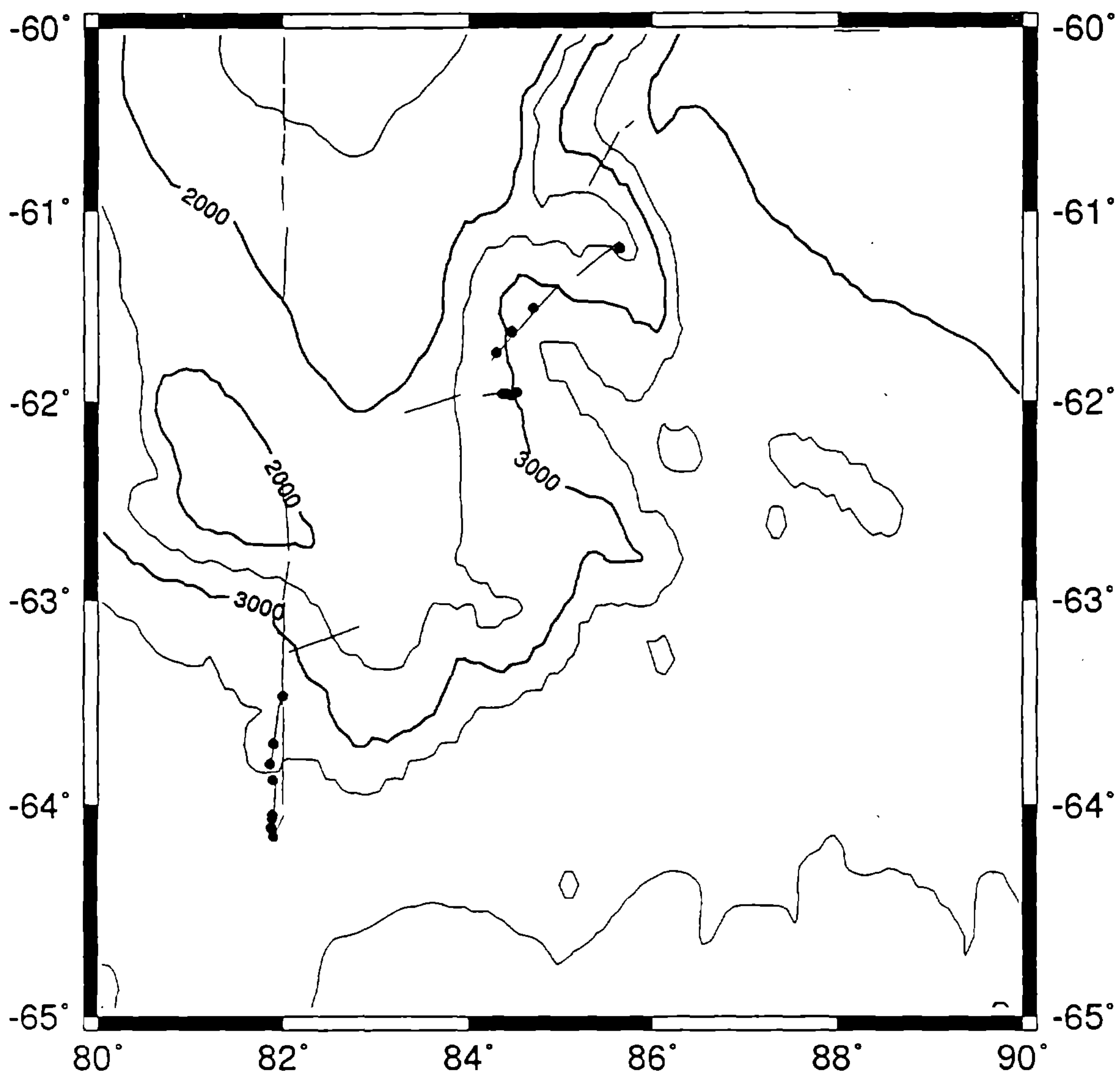

Figure 10.--The distribution of minke whale ***(Balaenoptera acutorostrafa)*** sightings (0) on December 26-28, 1994 along the southeast corner of the Kerguelen Plateau and northern Princess Elizabeth Trough. Minke whales were observed near the ice edge at 82°E longitude and along a tongue of ice advected northward in a western boundary current on the southeastern flank of the Kerguelen Plateau. Continuous survey effort is represented by straight lines, connecting the position of the R.V. ***Knorr*** at the beginning and end of the survey periods. The variable orientation of the cruise track during the northward transit between 64°S and 60°S reflects the difficult navigation along an impenetrable tongue of ice.

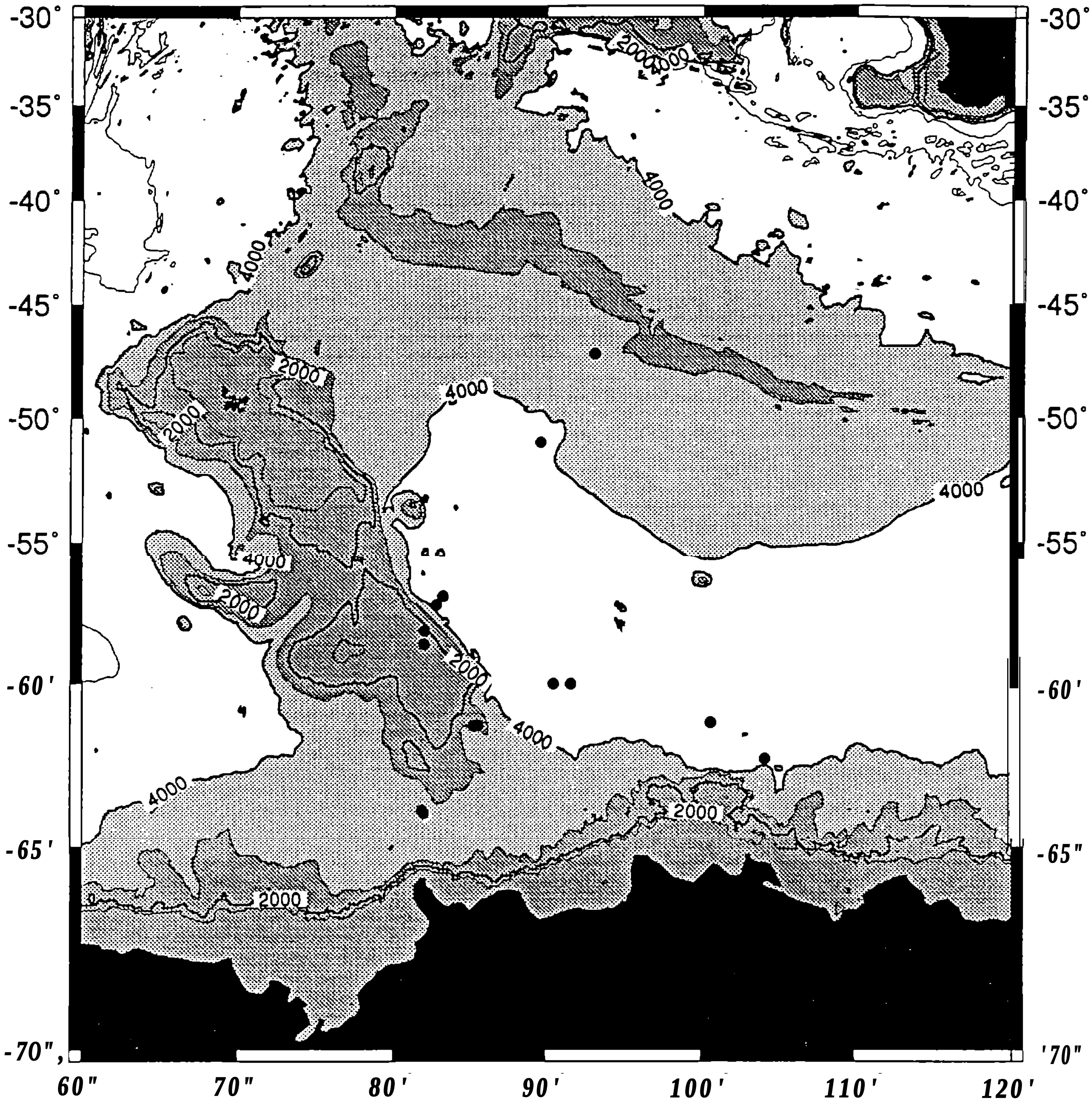

Figure 1l.--The distribution of humpback whale ***(Meguprera novueungliue)*** sightings (0) in the Southern Indian Ocean during WOCE I8, I9 from December 1, 1994 - January 19, 1995. Over half of all humpback sightings were associated with the Kerguelen Plateau and 87% of sightings were south of the Polar Front. The lack of any sightings of humpbacks during the northward leg (19) along 115°E suggests that humpbacks migrating from Western Australia do not head directly south, but rather approach high latitude on a southwesterly course.

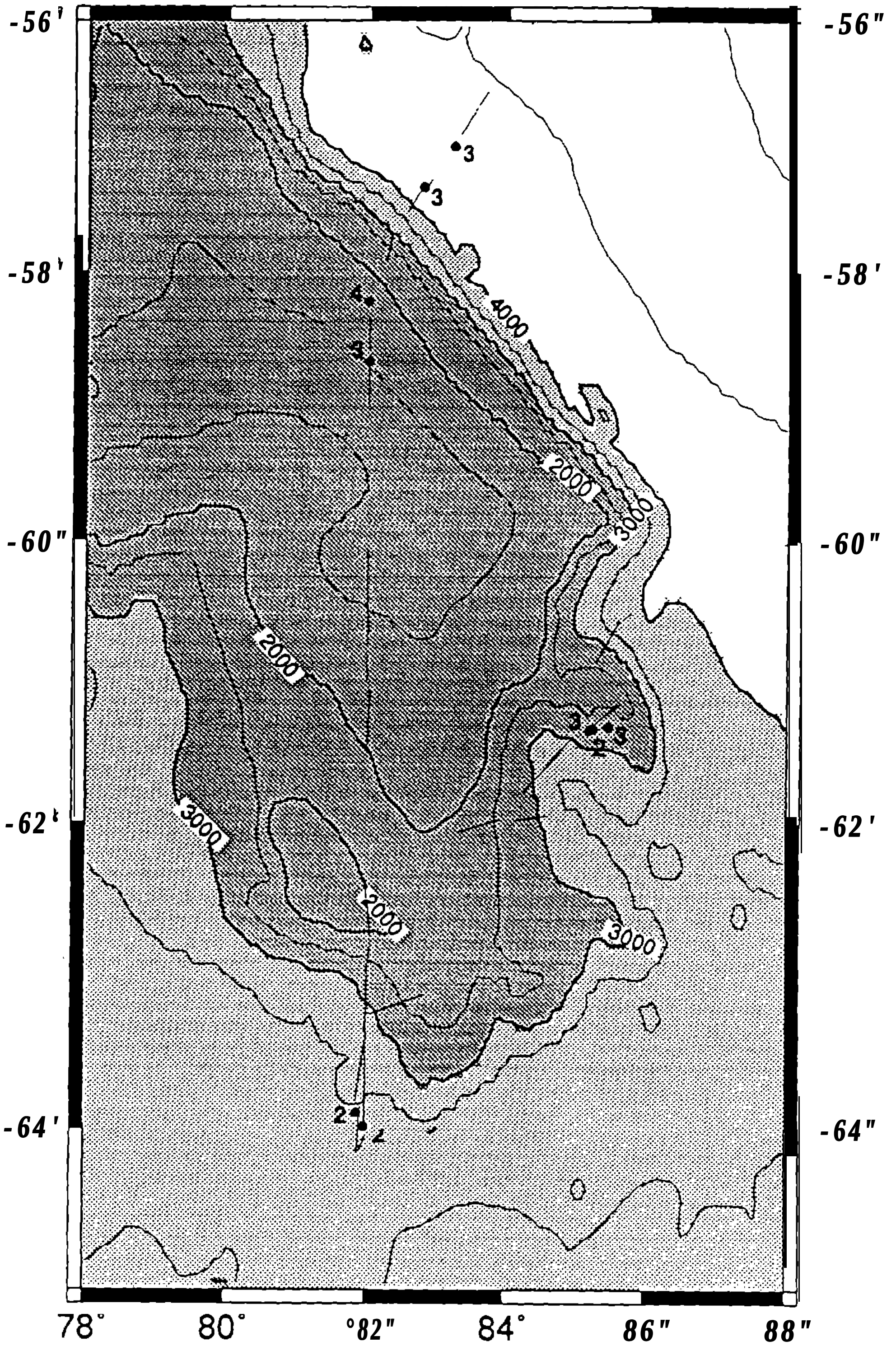

Figure 12.--The distribution of humpback whale ***(Megupteru novueungliue)*** sightings (m), and the number of whales per sighting, on December 23 - 28, 1994 along the southern and eastern edges of the Kerguelen Plateau and the northern Princess Elizabeth Trough. Humpbacks were observed as far south as the retreating ice (64°S). The increased frequency of sightings associated with the Kerguelen Plateau may reflect a preference for this environment. Continuous survey effort is represented by straight lines, connecting the position of the R.V. ***Knorr*** at the beginning and end of the survey periods. The variable orientation of the cruise track during the northward transit between 64°s and 60°s reflects the difficult navigation along a tongue of ice.

humpbacks approach high latitudes on a southwesterly course. In addition, the increased frequency of sightings associated with the Kerguelen Plateau may reflect a preference for this environment.

The southern bottlenose whale ***(Hyperoodon planifrons) was the*** fourth most abundant cetacean observed during the cruise. This species was observed within the full latitudinal range of the survey. The most northerly and southerly sightings occurred at 31.10°S and 64.44°S, corresponding to a temperature range at 5 m depth of greater than 16.0°C to 0.6°C, respectively. However, 81% of sightings occurred south of 60°S, either along or south of the mean position of the Southern ACC Front (Fig. 13). Unlike minke whales and sperm whales, this species was sighted in the deep Australian-Antarctic Basin (> 4000 m).

A total of five killer whale (Orcinus ***orcas)*** sightings were obtained during the cruise. Four of the five sightings occurred along the southeastern edge of the Kerguelen Plateau in iceberg-laden waters; these sightings, south of the Polar Front, were along the mean positions for the Southern ACC Front and Southern Boundary of the ACC (Fig. 14). This latter distributional pattern corresponds to the densest concentrations of minke whales and sperm whales (Figs. 6 and 9). At least one killer whale and three humpbacks were sighted together during a possible attack at 61.32°S; 85.48°E. One of the humpbacks had a consistently red blow (R. Pitman observation). The largest group of kitler whales (n=20) was observed at the northern edge of the Princess Elizabeth Trough (62.97°S; 82.00°E). In addition to the sightings off the Kerguelen Plateau, a group of eight killer whales was sighted along the shelf break off Southwestern Australia.

The effects of historical whaling on the abundance of large balaenopterids are still observed in the Southern Indian Ocean (Table 2). One off-effort sighting of a blue whale (B. musculus) was made in the Australian - Antarctic Basin (60.81°S; 99.46°E). In the same region (60.87°S; 99.65°E), another rare sighting of two southem right whales ***(Eubalaena australis)*** was obtained (Fig. 15). One pygmy blue whale (B. muicufus ***brevicauda)*** was observed in the South Australia Basin, north of

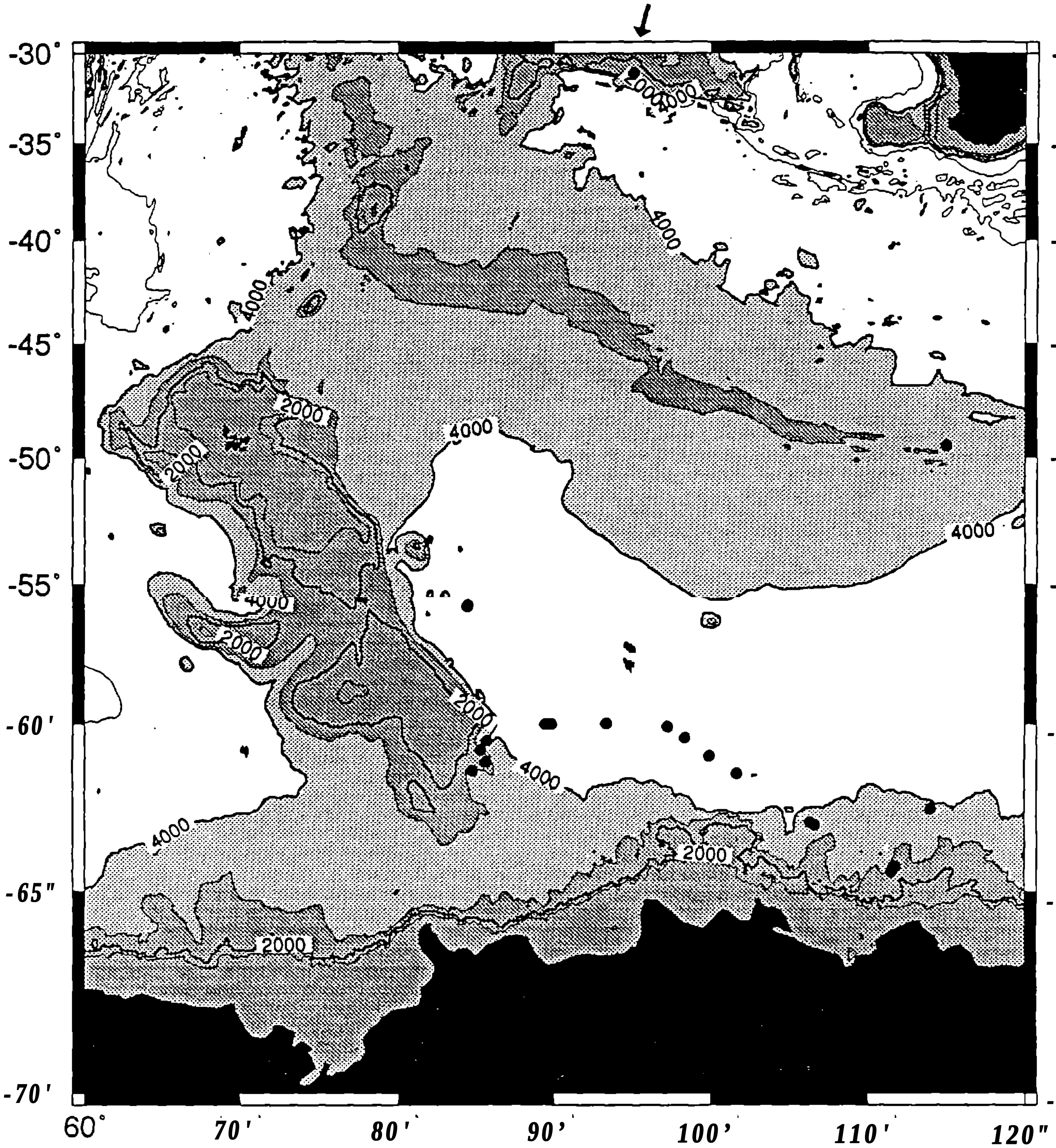

Figure 13.--The distribution of southern bottlenose whale ***(Hyperoodon planifions)*** sightings (0) in the Southern Indian Ocean during WOCE I8, I9 from December 1, 1994 - January 19, 1995. This species was observed within the full latitudinal range of the survey; however, 81% of sightings occurred south of 60°S, either along or south of the mean position of the Southern ACC Front.

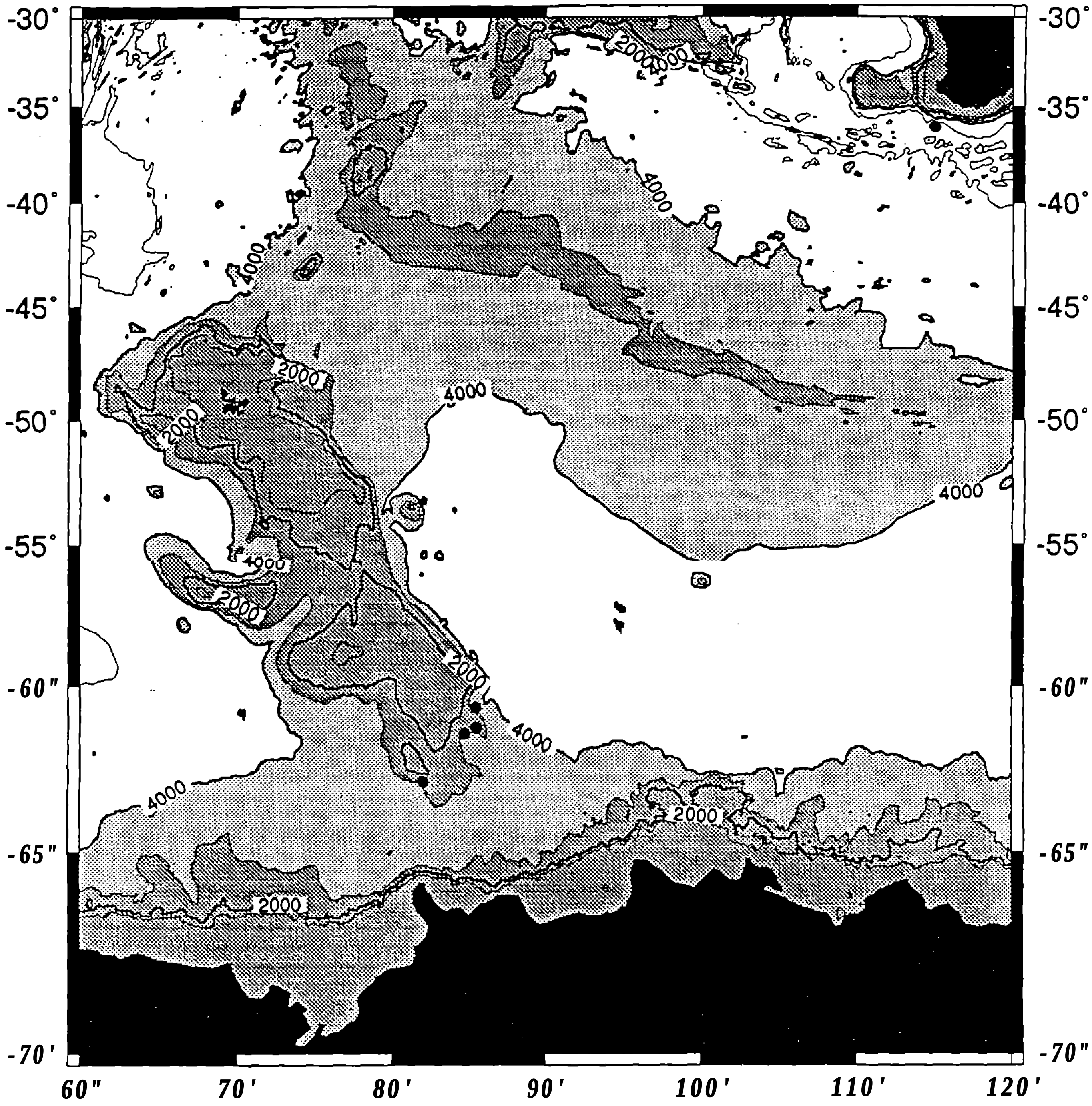

Figure 14.--The distribution of killer whale (Orcinus ***orca)*** sightings (0) in the Southern Indian Ocean during WOCE I8, I9 from December 1, 1994 - January 19, 1995, Four of the five sightings occurred in iceberg laden waters south of the Polar Front along the Southern ACC Front and Southern Boundary of the ACC off the southeastern edge of the Kerguelen Plateau.

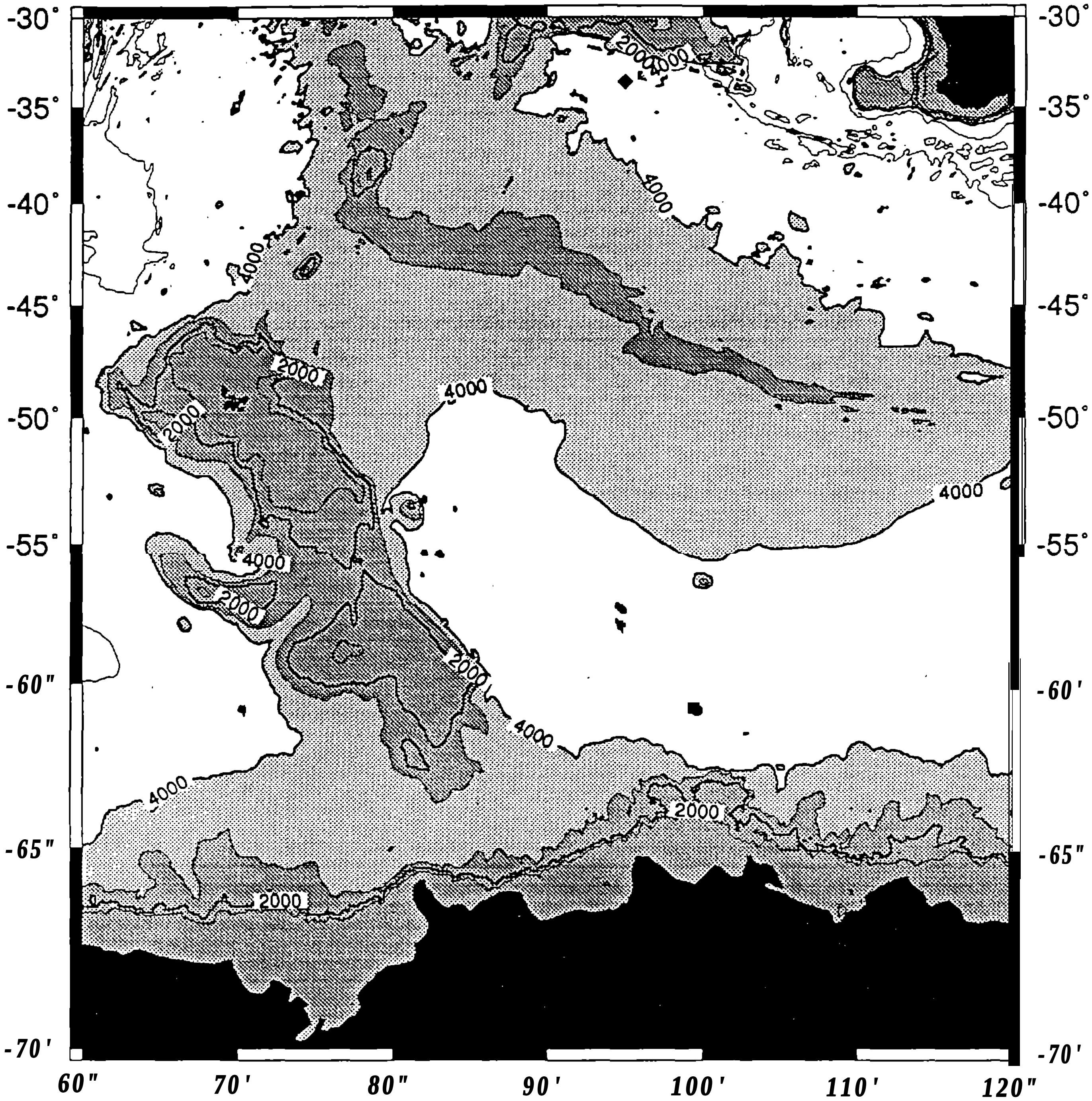

Figure 15.--Positions of sightings of rare balaehopterids in the Southern Indian Ocean during WOCE I8, I.9: one pygmy blue whale ***(Balaenoptera musculus brevi-caudu)*** (4) on December 7, 1994; one blue whale ***(Baluenopreru muscufus) (m),*** and ***two*** southern right whales ***(Eubaluenu uustrulis)*** (0) on December 30, 1994.

the Southeast Indian Ridge (33.60°S; 95.01°E). There were no confirmed sightings of fin whales ***(B. physalus)*** or sei whales ***(B. borealis).*** It is possible, however, that these species were represented under ***the categories*** of ***Balaenoptera*** spp. or unidentified large whale (Table 2). Given that the populations of blue whales and right whales in the Southern Indian Ocean are considered too severely depleted for feasible monitoring (Best, 1993). any sightings of these species are of great interest.

Distribution of Cetacean Sightings Relative to Bathymetry

The distribution of sightings relative to bathymetry and frontal zones is plotted in Figure 5. Sightings of cetaceans were more numerous during the south-bound, western leg (18S, between 82°-95°E) than during the northward, eastern leg (I9S, along 115°E). There was more shallow ocean basin (< 4000 m) along the western leg than the eastern leg; the western leg passed over the Kerguelen Plateau and a broader region of the Southeast Indian Ridge. The highest densities of cetaceans were observed over the complex edge topography along the southern flank of the Kerguelen Plateau (Fig. 5). Average densities for the two most abundant species in this region, ***the*** sperm whale ***(Physeter macrocephalus)*** and the minke whale ***(Balaenoptera ucutorostrata),*** were 1.3 and 1.6 whales 100 km^2, respectively (Table 2). Data for other species were insufficient for estimating densities; however, the distribution of sightings of humpback and killer whales suggests that these species are also more abundant in the vicinity of the Kerguelen Plateau.

Sperm whales congregated either directly over, or near, complex batbymetry, such as the edge of the Kerguelen Plateau and Princess Elizabeth Trough (Figs. 6 and 7), and the shelf/slope region off southwestern Australia (Fig. 8). This wide geographic split in the population arises from the migration of males to high latitude in the Antarctic zone during the austral summer, while females and immature animals remain in warmer waters at lower latitude. Despite the large latitudinal separation in the population, this species clearly appears to prefer habitat which includes steep, complex topography with proximity to deep water between 2000-4000 m.

Cetacean Distributions Relative to Frontal Zones and Circulation

The distribution of cetacean sightings relative to the mean position of four frontal zones is shown in Figure 5. The STF did not appear to attract higher numbers of cetaceans than either of the zones to the north or south, the Subtropical Zone and the Subantarctic Zone, respectively. The importance of the two ACC fronts, the SAF and the Polar Front, to cetacean habitat is less clear. Limited survey coverage due to adverse weather conditions, especially across the Polar Front, hindered even qualitative assessment. Weather, and consequently survey effort, improved south of 55°S . The highest densities of cetaceans, which occurred along the southern flank of the Kerguelen Plateau, align with the mean position of the Southern ACC Front and southern water mass boundary of the ACC (Fig. 5). The front is a current core of the ACC, whereas the southern boundary of the ACC delineates the southern-most extent of a water mass, Circumpolar Deep Water (Orsi et al., 1995). South of the Kerguelen Plateau these two features occur in close proximity (Fig. 5). The front and boundary are topographically steered around the southern comer of the Kerguelen Plateau, making it difficult to separate the influences of the circulation from the effects of complex topography on cetacean habitat. In addition, a western boundary current along the southeastern flank of the Kerguelen Plateau directs and advects the retreating ice in a pattern similar to the Southern ACC Front and southern water mass boundary of the ACC (compare Figs. 3 and 5).

Results from the Acoustic Doppler Current Profiler (ADCP) document the large mesoscale variability in the circulation of the Southern Indian Ocean. The confused, powerful, meandering flows associated with the zonal jets of the ACC are shown in Figure 16 (provided by E. Firing, U. of Hawaii). Current speeds are reduced or moderate across the Kerguelen Plateau and near the retreating ice (Fig. 17, provided by E. Firing, U. of Hawaii). Evidence of the northward flow of a western boundary current along the eastern flank of the Kerguelen Plateau can be seen in the vectors at 62°S; 85°E. The highest concentrations of cetaceans, associated with the edge of the Kerguelen Plateau and proximity to the retreating ice, occur in sluggish or moderate surface flow of 30 cm s^{-1} or less. There is some suggestion of eddying near the ice

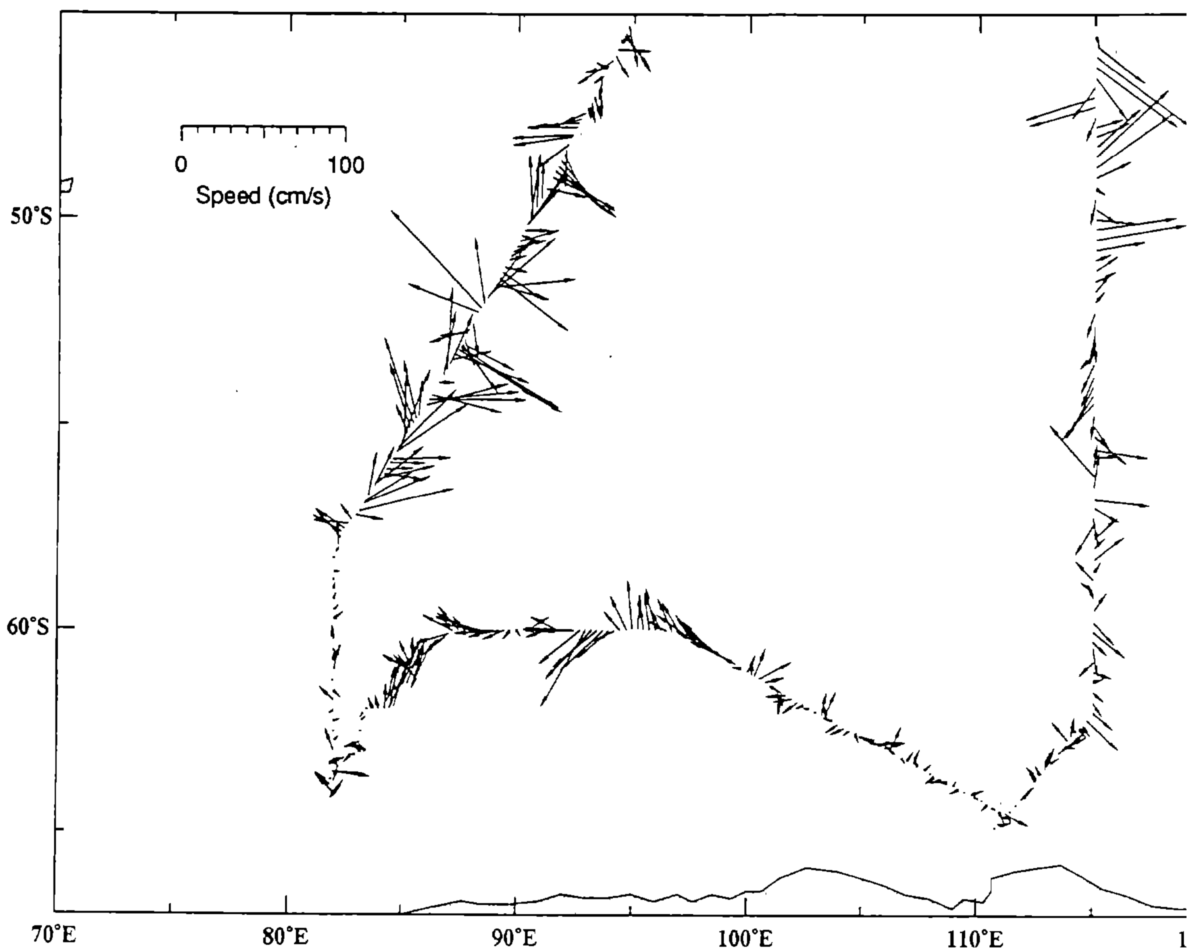

Figure 16.--Current velocity at 125 m to 175 m during WOCE I8, I9, as determined from a shipboard Acoustic Doppler Current Profiler (ADCP). Vectors show the strong mesoscale variability in the Antarctic Circumpolar Current, the weak circulation over the Kerguelen Plateau, the northwestern flow of the Western Boundary Current on the southeastern flank of the Kerguelen Plateau, and the weak currents observed during the second approach to the ice edge at 110°E. This figure was provided by Eric Firing (U. of Hawaii).

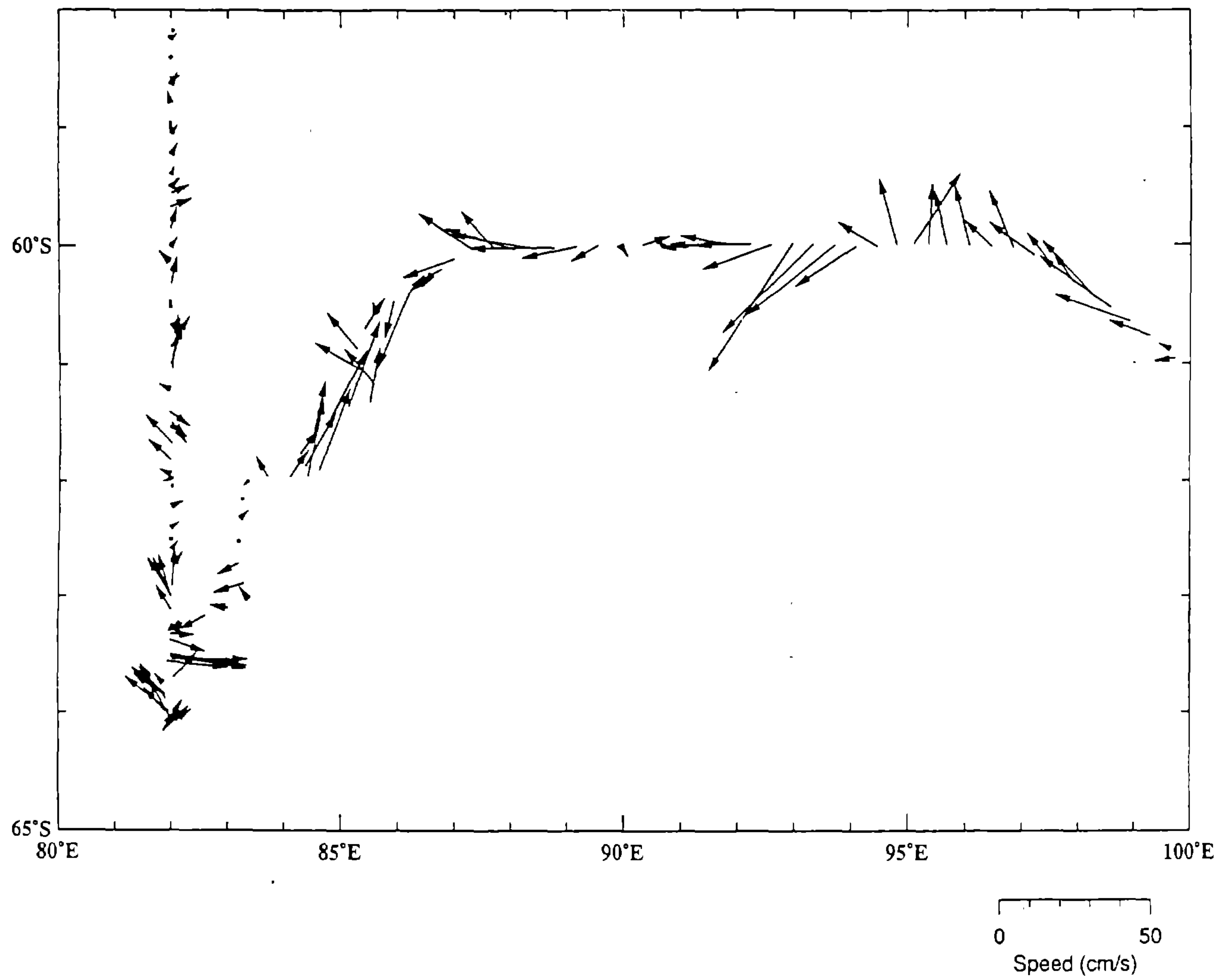

Figure 17.--Current velocity at 175 m to 225 m during WOCE I8, I9, as determined from a shipboard Acoustic Doppler Current Profiler (ADCP). Vectors show the sluggish circulation over the Kerguelen Plateau and the northwestern flow of the Western Boundary Current on the southeastern flank of the Kerguelen Plateau. The currents suggest the presence of an eddy at 64°S, 82°E, at the end of hydroleg I8. This figure was provided by Eric Firing (U. of Hawaii).

edge at the southern most extent of leg I8s in the Princess Elizabeth Trough.

Cetacean Distributions and the Ice Edge

On December 24, 1994, the first iceberg was encountered north of the Kerguelen Plateau at 57.30°S; 82.83°E. This iceberg was among those advected northward by a western boundary current along the eastern flank of the Kerguelen Plateau. The position of the retreating ice edge, as evident in satellite images for December 1 and December 29, also reflects the influence of a western boundary current (Pig. 3). A tongue of ice extended northward along the southeastern comer of the plateau, carrying and spawning the icebergs observed further north. The southward survey line along 82°E longitude. and the return northward leg from 64°S back to 60°S, paralleled the impenetrable northward advected ice. The highest densities of sperm whales and minke whales were found in navigable waters along the western side of the tongue of northward advecting ice.

The R.V. ***Knorr*** is not an ice breaker and was incapable of entering pack ice. The ship therefore had to maneuver carefully through the marginal ice edge zone and parallel the tongue of ice advecting northward. The ice edge was encountered at the end of line I8s at 64.15°S; 81.8°E. The patterns of the distributions of three species suggest that proximity to drift ice or the ice edge provided valuable cetacean habitat. Sperm whales, ***(P. macrocephalus), minke*** whales ***(B. acutorostrata),*** and killer whales (0. ***orca),*** were most densely concentrated at the southeastern comer of the Kerguelen Plateau, south of 61°S, in surface waters carrying numerous icebergs (Figs. 6, 9, and 14 respectively).

Minke whales have been associated with new ice and pancake ice in all seasons (Ribic et al., 1991). In the present study, Minke whales were also most dense within the marginal ice zone. The distribution of sperm whales was very similar to that of minke whales off the southeastern corner of the Kerguelen Plateau, although minke whales were typically closer to the ice edge than sperm whales. The similarity in the broad distributions of these two cetacean species, which occupy separate trophic niches, suggests that diverse processes contribute to the availability of euphausiids, squid, and fish in this region.

All of the following features and processes can contribute to enhanced primary production, secondary production, or prey availability off the southeast comer of the Kerguelen Plateau and in the northern portion of the Princess Elizabeth Trough: higher spring primary production associated with the marginal ice zone and the tongue of ice which is steered northward along the east side of the plateau; the presence of shoaled UCDW and higher macronutrient concentrations between 200-400 m at the southern boundary of the ACC; the potential for Ekman upwelling at the Antarctic Divergence to bring UCDW within the surface mixed layer; upwelling in eddies associated with the Southern ACC Front or southern boundary of the ACC; and topographic shoaling of UCDW along the flank of the Kerguelen Plateau.

Although the December distribution of humpback sightings does not suggest that this species prefers the marginal ice zone, humpbacks were occasionally observed within meters of large icebergs. A group of four humpbacks in the Australian-Antarctic Basin (60.00°S; 91.59°E) swam over to a large iceberg and remained within the swell up against the side of the ice. It is not known whether the ice provides a sense of refuge for the whales, or whether it relates to the availability of ice-associated prey.

Proximity to the ice edge is not a uniform predictor of suitable cetacean habitat. Cetaceans were frequently sighted during the first approach to the ice edge at 82°E, along the edge of the Kerguelen Plateau; however, few cetaceans were sighted during the second approach to the ice edge at 64.87°S, 110.85°E (Fig. 3). After crossing Petersen Bank and reaching the pack ice, we observed only three minke whales, four southern bottlenosed whales, one ***Amoux's*** beaked whale ***(Berardius arnouxii),*** and one unidentified beaked whale. There were no sightings of sperm whales, humpback or killer whales in this region. Although fog, snow and high winds limited survey effort during the second approach to the ice edge (Fig. 4). periods of calm weather and good visibility did not reveal the same assemblages or concentrations of cetace- MS found in association with the flank of the Kerguelen Plateau, or northern region of the Princess Elizabeth Trough. Therefore, it is proposed that the combination of complex bathymetry, currents, position of the Southern Front and Southern Boundary of the ACC, associated shoaling of Upper Circumpolar Deep Water, and proximity to the ice edge, generates uniquely favorable conditions for cetaceans at the southeast comer of the Kerguelen Plateau.

Observations of Seals

Although the survey methods were not designed to study the pelagic distributions of seals, fur seals were consistently recorded when sighted. In addition, the positions of CTD stations where seals were observed around the ship were also recorded. When it was impossible to identify a seal to species, the description was entered as unidentified fur seal. There were only ten sightings of fur seals during the cruise (Table 5); however, these mapped observations contribute significantly to the sparse data on pelagic distributions and ranges of fur seals (Fig. 18).

There were no sightings of fur seals south of the Polar Front. The Subantarctic fur ***seal Arctocephalus tropicalis was*** not observed south of 47.45°s. During WOCE legs I8S and I9S, this species was observed along both longitudinal transects at 95°E and 115°E (Fig. 16) north of the Polar Front. In general, this species does not breed south of the Polar Front (Kerley, 1984). However, in 1987 the first pupping record of ***A. tropicalis*** was recorded from Heard Island, south of the Polar Front (Goldsworthy and Shaughnessy, 1989).

It is possible that the seals sighted in the South Australian Basin and over the Southeast Indian Ridge belong to the closest populations of ***A. tropicalis*** breeding on Amsterdam or St. Paul Islands. Most sightings of ***A. tropicalis*** on the Australian continent have been immature animals, typically in poor body condition (Gales et al., 1992). These seals were thought to originate from Iles Amsterdam or Macquarie Island, suggesting a wide dispersal of young animals from natal sites. The pelagic range of this species however is poorly understood, and it is possible that the seals observed during the WOCE cruise may have originated from populations breeding on other Southern Indian Ocean islands: Prince Edward Islands and Iles Crozet. Islands

Table S.--Pinniped sightings during WOCE I8, I9 Southern Indian Ocean.

Species	Latitude °S	Longitude°E
Arctocephalus tropicalis (Gray, 1872) (Subantarctic fur seal)	38.489	95.006
	40.108	95.001
	45.467	94.619
	47.445	92.878
	42.128	114.997
	40.239	114.987
Arctocephalus gazella (Peters, 1875) (Antarctic fur seal)	49.964	90.591
Unidentified fur seal	42.267	95.011
	47.009	114.983
	43.506	115.000
Hydrurga leptonyx (de Blainville, 1820) (Leopard seal)	61.912	84.701

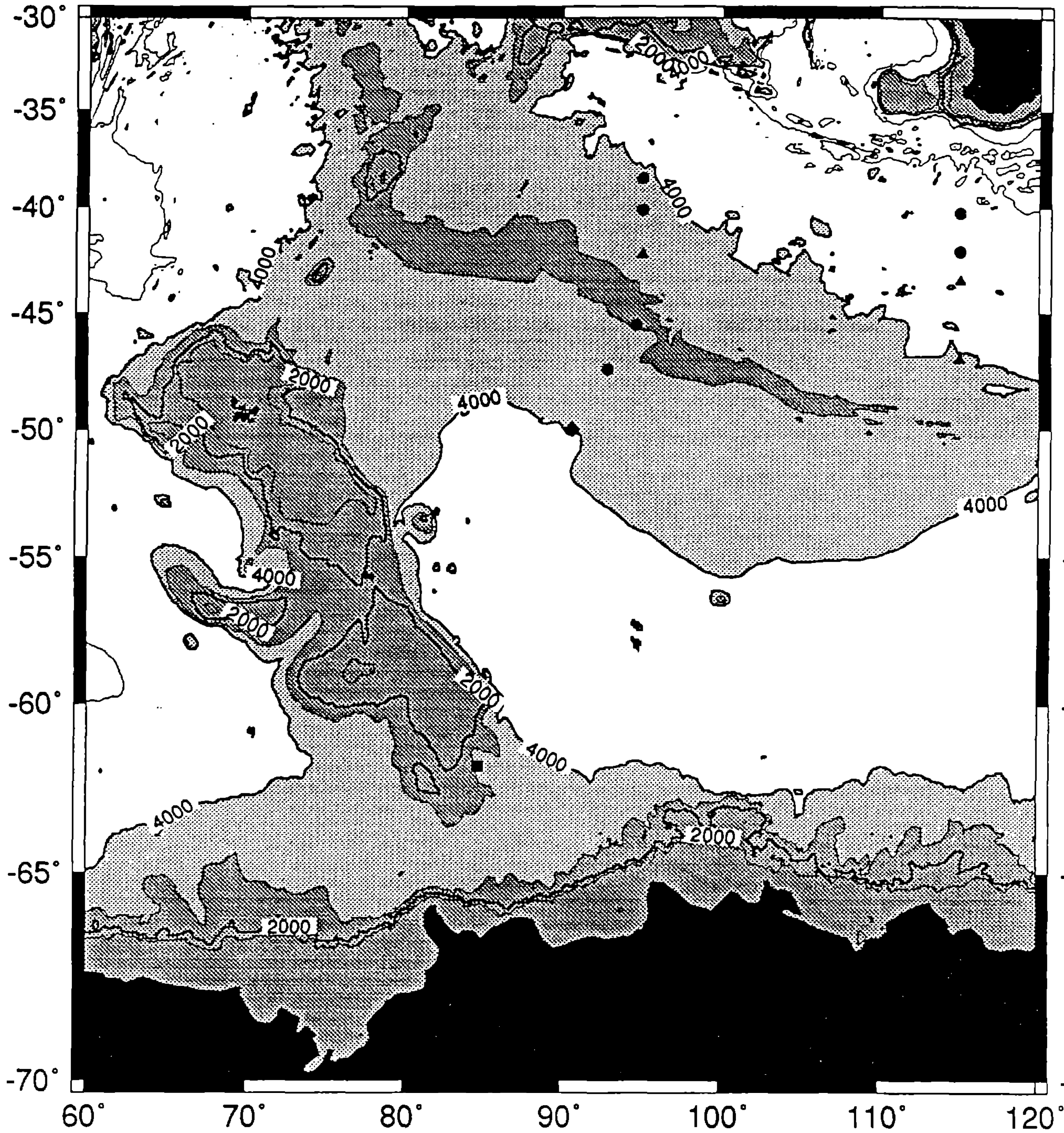

Figure 18.--The distribution of seal sightings in the Southern Indian Ocean during WOCE 18, I9 from December 1, 1994 - January 19, 1995: Subantarctic fur seal ***(Arctocephalus tropicalis)*** (0); Antarctic fur seal ***(A. gazella)*** (+); unidentified fur seals ***(A);*** and Leopard ***seal (Hydrurgu leptonyx) (m). All*** six sightings of ***A. tropicalis*** were north of the Polar Front. The one sighting of ***A. gazella was*** in the confused circulation of the Polar Front.

with reported colonies of this species span 180° in the Southern Ocean, from Tristan da Gunha and Gough Island in the Southern Atlantic eastward to Macquarie Island in the Southern Indian Ocean. Research is needed to delineate the pelagic ranges and inter-island movements of seals from each of the colonies.

Due ***to the*** difficulty ***in*** separating ***A. tropicalis*** from the Antarctic fur seal ***A. gazella*** in the field, it is possible that the sightings north of 47°S, categorized as unidentified fur seal, could have been either species. There was only one sighting of ***A. gazella*** in the region of the confused circulation of' the Polar Front. This sighting at 49.96°S is within ***the*** latitudinal range for ***this*** species. ***Arctocephalus gazella was*** abundant at Kerguelen Island during the nineteenth century and presently breeds on both Kerguelen and Heard Islands (Bester, 1984). Sightings of fur seals over the Kerguelen Plateau have been compiled by Ensor and Shaughnessy (1990). but few animals were identified to species.

The fringes of the pack ice along 82°E and 111°E were remarkably depauperate of seals. With the exception of one sighting of a leopard ***seal (Hydrurga leptonyx)*** on the ice off the. southeast comer of the Kerguelen Plateau (Fig. I8), there were no sightings of ice seals. The leopard seal was on the unnavigable tongue of ice advecting northward with the western boundary current.

DISCUSSION

Sperm Whale Distribution in the Southern Indian Ocean

Historical whaling records may provide evidence for preferred cetacean habitat in an ocean now depauperate in large whales. Townsend's (1935) global maps of American whale catches from 1761 to 1920 are one source of historical distributions. These maps of assembled catch positions provide excellent coverage of sperm whale catches north of 40°s. Farther south, however, the maps are blank, perhaps due to an avoidance of high latitude on the part of vessel captains. Therefore, Townsend's (1935) maps provide no historical information on the high latitude habitat of sperm whales. Townsend's map does confirm the historical abundance of sperm whales off southwestern Australia along with some catches near St. Paul and Kerguelen Islands. Aerial surveys in the 1960s also documented the presence of sperm whales along the edge of the Australian continental shelf from 113°E, south of Cape Leeuwin, to 127°E (Bannister, 1968). The sperm whales observed during the present cruise along the Australian shelf break at 115°E verify the continued use of this habitat.

There are few maps of the Southern Ocean distribution of sperm whales. Maps of Brown et al. (1974) exclude the high latitude distribution of sperm whales. However, the cetaces assessment cruises under the International Whaling Commission's International Decade of Cetacean Research (IWC/IDCR) in 1978/79 for area IV (70°E - 130°E) in the Southern Indian Ocean obtained 72 sightings of sperm whales south of 58°S (Kasamatsu et al., 1988). During the latter cruises, sperm whales 'were seen on occasion within 200 m of the pack ice edge. This was also observed during the present survey.

During WOCE section I8, the highest concentrations of sperm whales occurred along the southeast corner of the Kerguelen Plateau. This distribution is not apparent on the sighting map of Kasamatsu et al. (1988), despite the apparent survey coverage in this region. However, positions of Norwegian sperm whale catches during four seasons in the 1950s show more whales taken south of the Kerguelen Plateau (60°S) and between 80° - 90°E than in adjacent 10° longitude segments (Holm and Jonsgard, 1959). Therefore, the summer presence of sperm whales as far south as the receding ice in the southeast Indian Ocean, and in the vicinity of the Kerguelen Plateau, has been documentedfor at least the past four decades. However, the following description of the oceanographic processes which contributed to the observed 1994/1995 concentrations of sperm whales off the southeast comer of the Kerguelen Plateau is a new contribution to Antarctic cetacean ecology.

Sperm Whales, the Southern Boundary and Southern Front of the ACC

The mapped positions of sperm whales observed south of the Kerguelen Plateau fall roughly along the Southern ACC Front and the Southern Boundary of the ACC. South of the Kerguelen Plateau, these two features are in close proximity due to topographic steering of the currents. The Kerguelen Plateau forms a north-south aligned obstacle to the eastward flow of the ACC, and topographically steers the southern water mass boundary and front of the ACC further south into higher latitudes than in adjacent basins (Orsi et al., 1995). The southern water mass boundary of the ACC has recently been defined as the poleward extent of UCDW (Orsi et al., 1995). The latter water mass, characterized by warmer temperature, higher salinity, lower oxygen, higher CO, and higher macronutrient concentrations (phosphate, silicate, nitrate), originates at lower latitudes and shoals southward beneath northward flowing Antarctic Surface Water and Antarctic Intermediate Water (Fig. 1).

As UCDW nears the surface at high latitude around the Antarctic continent, it may become entrained into the surface mixed layer. Along WOCE leg I8S, over a distance of 3000 km, UCDW shoaled from a depth of 2400 m at 40°S latitude to less than 400 m at the southern water mass boundary of the ACC at 64°s. The southward shoaling of UCDW and its possible entrainment into the surface mixed layer at the Southern Boundary of the ACC may contribute directly to regional production and indirectly to enhanced cetacean densities at the southern end of the Kerguelen Plateau.

In general, nutrients are not considered limiting to phytoplankton growth in Antarctic waters and are often not well correlated with chlorophyll pigment concentration (Comiso et al., 1993). This paradox may be explained by the deficiency of iron available to phytoplankton in Antarctic waters (Martin et al., 1990). Local iron enrichment may be an important factor determining the spatial variability in phytoplsnkton production in regions otherwise rich in nutrients (de Baar et al., 1995). Although the role of iron in Antarctic phytoplankton growth may not be completely resolved, any process which contributes to the shoaling or upwelling of trace element-enriched water would be expected to have important regional effects on primary production. The concentrations of trace elements in UCDW, however, are unknown. To summarize, at the Southern Boundary of the ACC, UCDW shoals to a depth of less than 400 m, providing a subsurface source of macronutrients that may be upwelled or otherwise mixed into the surface mixed layer.

In addition to transporting macronutrients to high latitude, shoaling CDW may also carry bathypelagic and mesopelagic prey species of sperm whales (cephalopods and fishes). The sperm whale is a mesopelagic macroteuthophage; it is virtually the only occupant of this niche, with the possible exception of some beaked whales (Rice, 1989). It has been suggested that sperm whales migrate south in the southern hemisphere to follow cephalopods moving to high latitude with deeper, warmer and more saline water (Kirpichnikov, 1950; Benin, 1972). Therefore, it is proposed that sperm whales congregate around Antarctica at the southern water mass boundary of the ACC, where UCDW reaches its poleward extent and has shoaled to its shallowest depth. The alteration in the path of the circulation of the ACC around the Kerguelen Plateau would explain the congregation of sperm whales along the southeastern corner of the plateau and in the northern part of the Princess Elizabeth Trough. In this region the southern boundary of the ACC closely approaches the Antarctic shelf, yet occurs over complex bathymetry and depths greater than 3500 m in the Princess Elizabeth Trough. The combination of shoaled UCDW and complex bathymetry may contribute to sperm whale foraging in this region.

Zones of convergence have been suggested to provide suitable sperm whale habitat due to the supply of sinking organic matter and the development of large deep water fauna (Berzin, 1972). The southern water mass boundary of the ACC, however, is not connected with a process of convergence. Instead, the most southern extent of the ACC is more closely **connected** to the Antarctic Divergence, the region where prevailing winds change from eastward to westward near the Antarctic continent. Where the southern water mass boundary of the ACC occurs near the Antarctic Divergence, there is the potential for Ekman upwelling to further bring UCDW and higher concentrations of macronutrients closer to the surface. Additionally, the steerage of the ACC and water masses around the flanks of the Kerguelen Plateau can cause shoaling of a deeper water mass without upwelling. Therefore, there are two mechanisms in addition to the meridional (north-south) shoaling of UCDW and entrainment into the mixed layer which could further bring macronutrients, and potential prey, closer to the surface.

The Southern Boundary of the Antarctic Circumpolar Current, the Ice Edge, and Balaenopterids

The coupling of several physical processes may explain why species such as sperm whales and Minke whales, which feed quite distinct trophically, occur in the same vicinity off the southeast comer of the Kerquelen Plateau. Sperm whales are presumably feeding either on mesopelagic squids and fishes which have been advected from lower latitude within Circumpolar Deep Water and now occur at shallower depth (200-400 m), or on deepwater prey exclusive to high latitude. For example, the gigantic cranciid squid, ***Mesonychoteuthis hamiltoni,*** is a dominant species in the diet of Antarctic sperm whales (Rodhouse and White, 1995; Pascoe et al., 1990; Clarke, 1980). Minke whales however feed on euphausiids, which rely either on: primary production enhanced by macronutrient enrichment supplied by shoaled UCDW at the Southern Boundary of the ***ACC*** (C.T.T., in prep.); phytoplankton blooms associated with the marginal ice edge zone along the retreating ice; or ice-associated algae. The physical processes associated with nutrient or trace metal availability at the Southern Boundary of the ACC should benefit balaenopterids indirectly via enhanced secondary production (i.e. krill). The Discovery expeditions found principal concentrations of Antarctic krill in the westward-flowing East Wind drift, and the eastward-flowing Weddell drift (Marr, 1962); in the Southern Indian Ocean, the region between the East and West wind drifts, or Antarctic Divergence, aligns with the newly defined Southern Boundary of the ACC (Orsi et al., 1995). In addition, along the southeast comer of the Kerguelen Plateau, the Southern Boundary of the ACC and the northern edge of the retreating ice are very similar, due to topographic steering of the currents. Balaenopterids could therefore benefit from the concomitant occurrence of several physical processes which force biological production: dynamics of the Southern Front and Southern Boundary of the ACC; pattern and position of the ice edge; and upwelling at the Antarctic Divergence.

Phytoplankton blooms along the retreating ice edge of the Southern Ocean may produce up to two times the total production over the rest of the growing season (Smith and Nelson, 1986). It is well known that Minke whales inhabit the marginal ice edge zone (Ribic et al., 1991), where they are thought to benefit from the higher production and complex trophodynamics of these regions. Off the southeast comer of the Kerguelen Plateau, where the highest densities of Minke whales were observed, the ice retreats in a very irregular pattern. The Southern Front of the ACC, the southern-most current core of the ACC, turns sharply to the north along the east side of the Kerguelen Plateau, generating a western boundary current (Speer and Forbes, 1994). This current advects ice northward along the eastern flank of the plateau. The circulation therefore can prolong an ice-associated habitat at lower latitude along the eastern side of the Kerguelen Plateau.

Satellite imagery (U.S. Navy/NOAA Joint Ice Center) confirmed that the tongue of ice along the southeastern side of the Kerguelen Plateau extended as far north as 60°S in early December 1994. Minke whales were observed along the tongue of advected ice between 82° - 86°E, and occurred closer to the ice edge than sperm whales. However, Minke whales were much less abundant along the pack ice at 111°E, which suggests that the presence of ice alone is insufficient to predict habitat use. The higher densities of Minke whales off the southeast comer of the Kerguelen Plateau may result from a synergistic coupling of several physical processes. In addition to the enhanced phytoplankton bloom formation due to ice edge associated surface stratification, and the resupply of macronutrients from recently shoaled or upwelled UCDW, there are also eddies which could contribute to the complex mesoscale variability in the region.

The generation of mesoscale eddies along frontal zones can often entrain nutrients and subsurface populations of plankton to surface layers. Consequently, eddies often support communities of greater biomass and trophic complexity than surrounding waters. In the southern hemisphere the isopycnals (lines of constant density) of cyclonic (clockwise) eddies shoal toward the center and predictably can-y macronutrients to shallower depth. Cyclonic eddies have been reported at 65°S, 80°E (Smith et al., 1984), and southeast of the Kerguelen Plateau at approximately 82°E (Orsi et al., 1995). The latter, clockwise eddy is apparently generated from the Southern ACC Front. In addition, the upwelling zone of the Antarctic Divergence along 63/64°S in the Indian Ocean sector is composed of a street of cyclonic eddies which further upwells CDW to the surface (Walcatsuchi et al., 1994). During WOCE I8S, the ADCP-derived currents at 175 - 225 m suggested that an eddy existed at 82°E in December (Fig. 17). Such eddies could further upwell UCDW from 200 m toward the surface. Therefore, it is possible that the existence of eddies off the southeast comer of the Kerguelen Plateau, in addition to the processes previously discussed, contributed to nutrient resupply in this complex region,

Humpback Whale Migration

Townsend's maps (1935). based on compilations from American whaling logbooks, show no records of humpbacks taken in the Southern Indian Ocean (south of 40°S). However, there were predictably high catches of humpbacks between Broome and North West Cape along Western Australia as well as several whales taken near Kerguelen Island. In addition, from 1931-1962 there was extensive hunting of humpbacks south of 50°S, as documented in maps of pelagic catch data (Mizroch et al., 1992). The intensive hunting of humpbacks off Western Australia and in the Southern Ocean came to a close in 1963, following international regulation. The population which winters off Western Australia now appears to be recovering (Bannister, 1985).

Tagging operations prior to 1962 showed that humpbacks migrate from their winter distribution along western Australia to high latitude in summer, fanning out south of 60°S in feeding grounds between 75° - 105°E (Brown et al., 1974). The results of the present cruise show that over half of all humpbacks sighted were in association with the Kerguelen Plateau and 87% of sightings were south of the Polar Front (approximately 53°S). Although the general pattern of humpback migration in the southeast Indian Ocean has been determined (Brown et al., 1974; Mizroch et al., 1992), the oceanographic processes which contribute to the high latitude habitat preference have not been previously examined.

Maps of pelagic catch data from 1931-1962 (Mizroch et al., 1992) show that the highest catch of humpbacks from November to February occurred in the vicinity of the southeast Kerguelen Plateau and along a high latitude band south of 60°s. This distribution suggests the following new hypothesis. In the late spring and early summer, the southern extent of migrating humpbacks and other balaenopterids aligns with the Southern Boundary of the ACC (C.T.T., manuscript in preparation). As mentioned in earlier sections, the Southern Boundary of the ACC delineates the southern-most extent of UCDW, a warm water mass enriched in macronutrients. Hydrographic section I8s during the WOCE cruise revealed that the latter water mass had shoaled to a depth of 200-400 m over the Kerguelen Plateau and in the northern Princess Elizabeth Trough. Any processes which further inject UCDW into the surface mixed layer can potentially enhance primary production through macronutrient and trace element addition. Therefore, enhanced primary and secondary production in the vicinity of the Kerguelen Plateau and the Southern Boundary of the ACC may generate a cascade of production at higher trophic levels in the upper several hundred meters of the water column suitable for cetacean foraging. In addition, the shoaled UCDW may provide a warmer subsurface habitat. As the ice retreats throughout the summer, humpbacks and other balaenopterids are probably also able to take advantage of the productive waters of the marginal ice zone. Only late in the summer, when the retreating ice no longer restricts occupation of higher latitude, do whales leave the Southern Boundary of the ACC and occupy the continental shelves.

In summary, the close proximity of several hydrographic features may contribute to enhanced biological production and increased cetacean densities in the northem portion of the Princess Elizabeth Trough and the southeastern edge of the Kerguelen Plateau: the high latitude penetration and close proximity of the Southern Front and Southern Boundary of the ACC; the associated high latitude extent of shoaled, nutrient-rich UCDW; the potential for Ekman upwelling at the Antarctic Divergence; the alignment of the Southern Boundary with the Antarctic Divergence; the presence of clockwise eddies and associated shoaling of isopycnals; the presence of complex bathymetry; the influence of a western boundary current on the pattern of ice retreat; and the concomitant formation of the productive marginal ice edge zone.

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