NARWHAL DISTRIBUTION RELATIVE TO THERMAL SEA SURFACE TEMPERATURE BOUNDARIES.

By

David G. Barber

A Practicum Submitted
In Partial Fulfillment of the
Requirements for the Degree,
Master of Natural Resources Management

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A practicum submitted to the Faculty of Graduate Studies of the University of Manitoba in partial fulfillment of the requirements of the degree of Master of Natural Resources Management.

ABSTRACT

This report presents results from an analysis of the relationship between narwhal and thermal water mass boundary locations. Statistical analyses were applied to quantify the relationship between narwhal location and the location of thermal water mass boundaries in narwhal summer concentration areas in the eastern Canadian Arctic. A review of literature provides clarification on the nature of thermal water mass boundaries and describes results of similar habitat preference analyses conducted with other species. A positive correlation is observed between location and density of animals with thermal water mass boundary locations from aerial surveys conducted in 1984 but not in 1985. Reasons for discrepancy between the two years, based on distributional differences evidenced in each year, are discussed. Management implications and recommendations of these results conclude the report.

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CHAPTER 1.0: INTRODUCTION

The primary objective of this research is to investigate the relationship between narwhal and thermal water mass boundary locations, and to assess the utility of the observed relationships for narwhal management.

1.1 Problem Statement

To make informed decisions regarding narwhal management, deficiencies in our current understanding of narwhal and their habitat preferences must be overcome. We need to develop an understanding of narwhal preferred habitat; ascertain the factors which are important for re-occurrence of narwhal in the summering areas; and improve survey precision to allow accurate monitoring of population levels.

1.2 Background

The narwhal (*Monodon monoceros*) inhabits the Arctic and North Atlantic Oceans of northern Canada (Finley and Gibb 1982) . A large summer concentration occur in the eastern Canadian Arctic, within bounds generally described by: Davis Strait in the south, Peel Sound in the west, Alexandra Fiord in the north and the west coast of Greenland in the east (Mansfield et al. 1975; Davis et al. 1978). A traditional summering area for narwhal is found in the inlets and fiords south of Lancaster Sound (Fig. 1). Previous aerial surveys show that summer concentration areas are primarily confined to: Eclipse Sound (and associated inlets), Admiralty Inlet, Prince Regent Inlet, and Peel Sound (Fig. 1). Narwhal are found outside these areas but in reduced concentrations (J.T. Strong. Department of Fisheries and Oceans, 501 University Cres. Winnipeg, MB. unpubl. data).

Concern has been expressed by both resource managers and resource harvesters that commercial development of hydrocarbons and minerals in the Arctic pose a serious potential threat to narwhal (Mansfield et al. 1975; Smith et al. 1985). The Canadian Arctic Resources Committee (CARC) estimates 1000 marine passages per year in the Northwest Passage by the year 2000 (*in* Kingsley et al. 1985), substantially increasing the probability of narwhal marine vessel interactions.

Very little is known about narwhal because of the inaccessibility and short duration of the open water season in the summering areas. Population surveys are an important instrument for management of the species but survey precision is limited by a poor understanding of distribution within, and movement between, each of the summering areas.

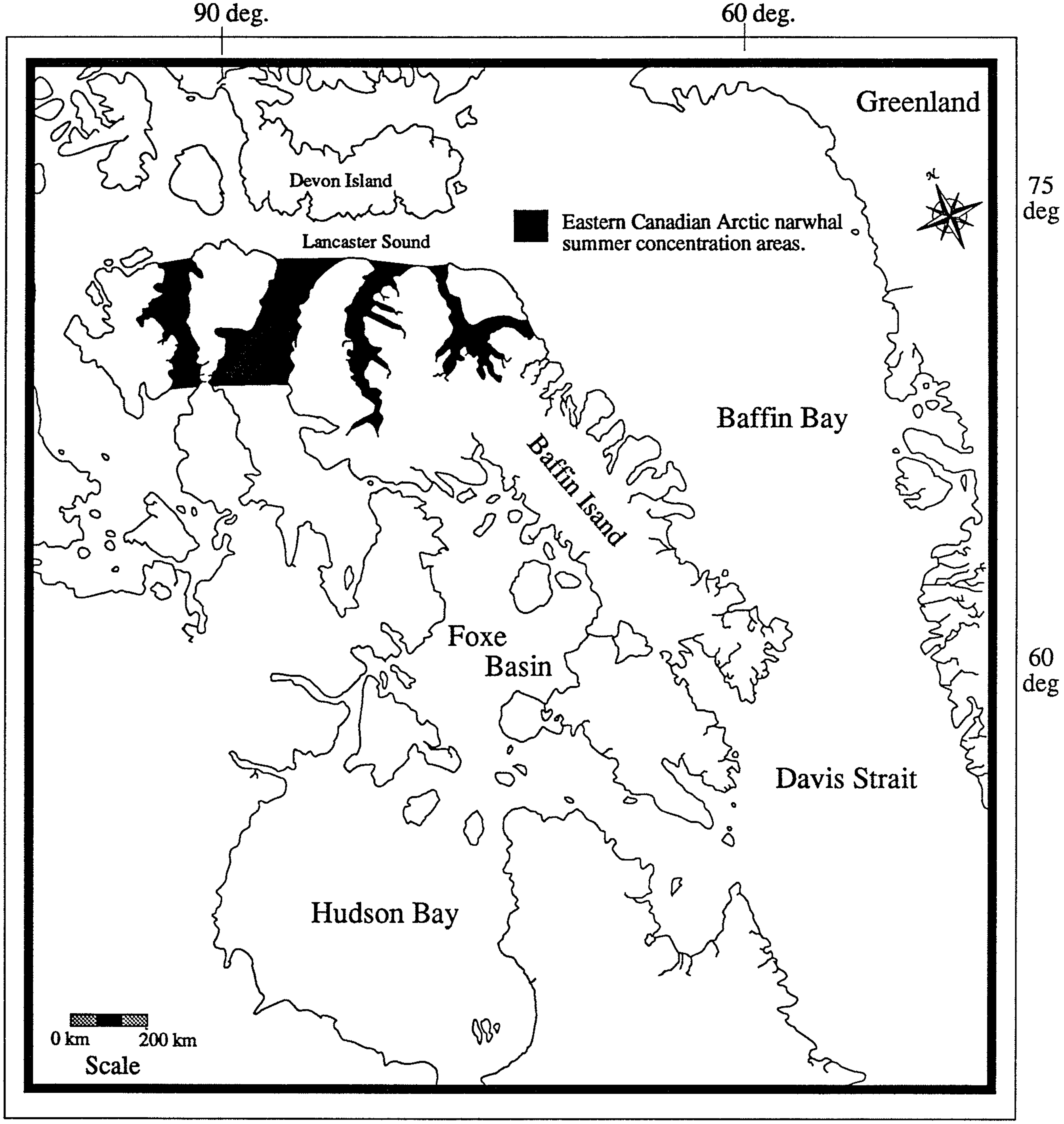

Figure 1. Eastern Canadian Arctic narwhal summer concentration areas.

1.21 Narwhal Population Surveys

Precise population estimates are essential for proper management of the species. Previous estimates by Tuck (1957) (*in* Mansfield et al. 1975) provide a minimum estimate of 6 000 based on counts of narwhal moving into Lancaster Sound, north of Bylot Island (Fig. 1). Mansfield et al. (1975) provides a "conservative estimate of 10 000", based on estimates by Tucker (1957) and Brummer (1971) (*in* Mansfield et al. 1975) for Canada and northwestern Greenland. Since 1975 several estimates have been obtained for areas frequented by narwhal. Davis et al. (1978) estimated a population between 20 000 and 30 000 for the eastern Canadian Arctic. Neither Mansfield nor Davis provided a statistical measure of precision for their estimates. A more recent survey by Smith et al. (1985) estimated a population level of 9 035 to 13 891 in Prince Regent Inlet and Lancaster Sound. To generate a narwhal estimate for the summering area Smith included estimates of 2 117 from surveys done by Fallis et al. (1983) in Admiralty Inlet. They combined these estimates, included a guess of 2 000 animals for Peel Sound, and obtained a population estimate of from 13 152 to 18 008 in the four narwhal summering areas (Fig. 1).

It is evident, from these previous surveys, that a precise narwhal population estimate in the summering areas is not available. The only survey which includes a measure of precision was done by Smith et al. (1985). Because they did not survey Admiralty Inlet, Eclipse Sound, or Peel Sound the estimate obtained should not be considered a baseline, appropriate for monitoring narwhal abundance in the future.

The Department of Fisheries and Oceans (DFO) is the federal agency charged with management of narwhal, including protection of habitat and control of harvest. Following recommendations by Fallis et al. (1983) and Smith et al. (1985), DFO conducted systematic aerial photographic surveys in the summering areas (Fig. 1) in August of 1983, 1984 and 1985 (Strong et al. unpubl. data).

1.22 Narwhal Distribution and Behaviour

Knowledge of animal behaviour and their movement both within and between summering areas is important for planning and interpreting population surveys and for clarifying the nature of narwhal habitat preference. Obtaining quantitative information on narwhal behaviour is difficult. Most of the previous work has been limited to sight specific behavioural studies or incidental observations of narwhal in each of the summering areas.

Narwhal behavioural observations have been recorded in Eclipse Sound (Silverman 1979; Finley and Gibb 1982) and Admiralty Inlet (Fallis et al. 1983). Observations of narwhal behaviour in Prince Regent Inlet or Peel Sound consist of incidental observations during aerial survey flights (Strong et al. unpubl. data; Smith et al. 1985). Mansfield et al. (1975) and Silverman (1979) indicate that narwhal engage in increased levels of social activity in Eclipse Sound and associated inlets, compared to activity at the ice edge earlier in the season. This increased social activity also was observed in Admiralty

Inlet (Fallis et al. 1983). Longitudinal studies of narwhal behaviour in Prince Regent Inlet or Peel Sound have not been conducted.

Finley and Gibb (1982) reported narwhal feeding on arctic cod (*Boreogadus saida*) at the ice edge and during movement through ice leads and cracks, into Pond Inlet and Eclipse Sound. They conclude the distribution of narwhal may, in part, be a function of arctic cod distribution and abundance. Examination of stomach contents from animals taken in the Inuit harvest (Finley and Gibb 1982; Hay 1984) revealed no evidence that narwhal were feeding in Eclipse Sound or Pond Inlet during the open water season. Contrary to this evidence, I observed an aggregation of beluga (*Delphinapterus leucas)*, narwhal, ringed seals (*Phoca Hispida*), harp seals (*Phoca groenlandicus*) and sea birds, in what has been described elsewhere (Finley and Gibb 1982) as a feeding aggregation, during aerial surveys of Peel Sound. Marine mammals in this aggregation displayed high levels of activity. Narwhal and beluga were observed in deep diving postures (fluke-out on the dive). A more detailed account of this observation will be reported by Strong et al. (unpubl. data)

Because the summering grounds cover such a large area, information on movement between and within each area has been obtained serendipitously. Fallis et al. (1983) observed fluctuations in the number of narwhal utilizing Admiralty Inlet both within and between survey years. Other researchers have also noted movement between areas within the summer season (Silverman 1979; Smith et al. 1985). The fact that animals move between areas is fairly clear, why they do, is not. It has been suggested that these fluctuations may be a function of ice distribution or prey species availability (Fallis et al.

1983). The only consistent observation of narwhal distribution within the summering areas consist of the trend for narwhal to locate far from shore (Mansfield et al. 1975; Finley 1976; Silverman 1979 and Campbell et al. 1988). This historical information has been supplemented in a more quantitative fashion by Richard et al. (Department of Fisheries and Oceans, 501 University Cres. Winnipeg, MB. unpubl. data) for narwhal in Repulse Bay, NWT. Data from four aerial surveys indicated that peak frequencies of narwhal occurred at distances greater than 4 km from the nearest shore.

1.23 Upwellings and Fronts; physical and biological characteristics

The thermal boundaries under investigation in this study are created by convergence and or divergence of water masses. Both upwellings and fronts delineate water masses of different physical and biological properties (Laevastu and Hayes 1981). At the surface, cold water of upwelling and frontal areas can be detected using remotely sensed images because of the contrast in emittance between water masses of different temperatures (Federov 1983). Appendix C describes the fundamental principles of remote sensing in the thermal infrared portion (9.0 μm to 12.0 μm) of the electromagnetic spectrum.

The physical dynamics of upwelling and frontal areas are characterized by the transport of nutrients (most importantly phosphate, nitrate, and silicate) from deep, cold water, up to the euphotic zone. Photosynthesis makes use of the nutrients to produce organic carbon. These areas of high primary production support a proliferation at other trophic levels because of the presence of primary organic material (Laevastu and Hayes 1981). It is therefore possible that narwhal presence at fronts and upwellings could be related to feeding. The convergence and divergence of water masses also causes surface borne materials to collect at these boundaries. This is an important consideration in the event of an oil or chemical spill in the narwhal summering areas.

Previous research provides illumination on the relationship between various trophic levels and the presence of upwellings or fronts. Remotely sensed images have been used to investigate the distribution and abundance of certain fish species in upwelling and frontal areas. Albacore tuna (*Thunnus alalunga*) abundance and migration were compared to the location and strength of a major front associated with the transition zone in the eastern North Pacific between subarctic and tropical water masses (Fiedler et al. 1984). Concentrations of migrating tuna were located in areas of frontal mixing and were absent in areas of uniform frontal sea surface features. Fiedler et al. (1984) found a further relationship between the strength of the frontal interface and tuna school size. He inferred more prey species were available to migrating tuna when frontal activity was pronounced. Laevastu and Hayes (1981) describe numerous studies that show a strong correlation between herring, capelin, blue fin tuna, and pilchard distributions, with the presence of upwellings and fronts. A particularly detailed study was conducted by Dietrich, Sahrhage and Schubert (*in* Laevastu and Hayes 1981). They summarized the important features affecting distribution of herring in the northern North Sea as:

- herring concentrate in the core of cold upwelling water.
- the lower the water temperature, the longer the herring remain.
- the geographical position of the upwelling varies spatially and temporally.
- daily vertical herring movement is influenced by thermocline structure.

The relationship between fish and thermal sea surface features is so well established many countries direct commercial fishing to areas of increased frontal or upwelling activity (Laevastu and Hayes 1981). The National Oceanographic and Atmospheric Administration (NOAA) provide sea surface temperature maps, produced from meteorological satellite thermal data, to the United States commercial fishing fleet. A substantial increase in the catch per unit effort has resulted (Fiedler et al. 1984).

Ornithologists have also investigated the spatial relationship between sea bird locations and oceanic fronts. Haney (1985) found a strong relationship between the presence of large and persistent oceanic fronts and the occurrence of phalaropes (*Phalaropus lobatus*). Haney states that these areas are important foraging habitat for post-breeding phalaropes because concentrations of primary organic material, particularly larval fish and copepod (*Eucalanus pileatus*), are present in higher concentrations at the front. Haney concludes that not only is there a strong co-occurrence of phalaropes and oceanic fronts, but also that seasonal phalarope abundance corresponds to frontal frequency and extent.

1.24 Habitat Preference

Habitat preference is important to many aspects of wildlife research, including management of habitat (Porter and Church 1987) and improved capability to monitor species abundance and distribution (Mendenhall et al. 1971). Knowledge of preferred habitat can be used in a stratification scheme to improve precision of population surveys, or alternately, to decrease the cost of obtaining current precision levels.

Few studies have documented the relationship between Arctic marine mammals and their habitat. Even fewer have addressed the question of narwhal habitat in the summering areas. The main problem in addressing habitat related questions is the difficulty and expense of obtaining information on Arctic marine mammal distribution coupled with habitat information. A popular method is to obtained habitat data concurrent with aerial surveys. Analysis is then conducted on the relationship between marine mammal locations and the location of habitat features. The typical objective of this research is to understand the characteristics of preferred habitat and determine how consistent the relationships are over time and space. This information is then used in a variety of activities relating to management of the species.

1.3 Research Objectives

The primary objective of this study is to investigate the spatial relationship between narwhal location and a single habitat parameter; the boundary between adjacent water masses of different temperature (i.e., thermal boundaries). Causal relationships are not considered since *in situ* data were not collected on the biological or physical nature of the thermal boundaries. If narwhal and thermal boundaries occur in the same spatial location (co-occur) and this co-occurrence is consistent spatially and temporally, the information would be useful as a stratification variable in future population surveys. The knowledge would also be a first step towards understanding narwhal habitat preference. To adequately address this objective four research questions are posed:

1) Is the spatial location of narwhal and thermal boundaries independent?

2) Can the result in (1) be exploited in a stratification scheme?

3) Is there a relationship between narwhal maturity class or sex class, and the minimum distance to thermal boundaries?

4) Does narwhal density change as a function of minimum distance to the nearest thermal boundary?

1.31 Research Question Rationale

Question one is fundamental to this investigation; do narwhal and thermal boundaries occur together more often than would be expected by chance? A positive co-occurrence of narwhal and boundaries infers that narwhal prefer to locate at or near thermal boundaries, but does not address the question of stratification based on the location of thermal boundaries.

The second question addresses the utility of a positive co-occurrence of narwhal and water mass boundaries for survey design. If narwhal and thermal boundary locations co-occur then knowledge of the distribution of these boundaries within the sample could be useful in planning aerial surveys. If thermal boundaries are distributed uniformly along all transects (i.e., uniformly throughout the sample) a systematic survey would be the most efficient sampling method. If boundaries are only found in a particular portion of each transect (i.e., a non-uniform distribution throughout the sample) then stratification based on the location of thermal boundaries would provide a more efficient sampling method. Stratification based on thermal boundary locations is possible since the boundaries can be located prior to conducting an aerial survey by either satellite or high altitude thermal surveys.

The third research question is directed at determining whether there is evidence of sex or maturity class segregation relative to preference for thermal boundaries. This research will contribute to our understanding of why animals use these areas.

In the first three questions spatial correlation is the parameter of interest. Due to social interactions among animals a binary variable of presence-absence is more appropriate for measuring spatial relationships (Pielou 1984). However, in stratification schemes density rather than occurrence of animals is usually the variable of interest. The effect of water mass boundaries on narwhal density therefore is considered separately (question four).

CHAPTER 2.0: METHODS

2.1 Study Area

The study area consists of four narwhal summering areas south of Lancaster sound (Fig. 1). Each of the areas is characterized by deep, cold Arctic waters, covered by sea ice approximately nine months of the year. Average prevailing currents are presented in Fig. 2. In an average year the ice edge in Lancaster Sound recedes east to a location north of Sommerset Island. Ice breakup in each of the four summering areas occurs near the end of July (Fallis et al. 1983).

2.2 Aerial Survey Data

Data from systematic aerial photographic surveys conducted in August 1984 and 1985 by Strong et al. (unpubl. data), were used in this investigation. A one-in-K systematic sampling design (Mendenhall et al. 1971) was used in Eclipse Sound, Admiralty Inlet, Prince Regent Inlet and Peel Sound (Figs. 3 and 4). Transects were oriented east-west, with a between transect spacing of eight minutes of latitude (Figs. 3 and 4). The survey platform was a DHC-6 Dehavilland Twin Otter equipped with an OMEGA navigation system, and barometric altimeter. The primary objectives of this three year study were to obtain a population estimate of narwhal inhabiting the summer concentration areas and to delineate their distribution. Complete results of the three year survey will be reported by Strong et al. (unpubl. data).

The 1984 and 1985 surveys were conducted using the Department of Fisheries and Oceans Remote Sensing System (Yaremchuk and Barber 1985). A Weild-Leitz RC8 large format aerial photographic camera was used to obtain information on narwhal. A Forward Looking Infrared (FLIR[1]) thermal imager was used to obtain information on thermal water mass boundaries.

2.21 Aerial photography

Each transect consisted of a line of photography with a swath width, perpendicular to transect orientation, of 1372 m. Photo exposure intervals were set using an electronic time intervelometer at a nominal underlap of five percent. Photography was collected using the following parameters:

- 228.6 mm by 228.6 mm film format.
- Kodak type 2445 aerial film (colour negative).
- Scale 1-to-6 000.
- Ground coverage = 1372 m by 1372 m.
- Aircraft altitude = 914 m

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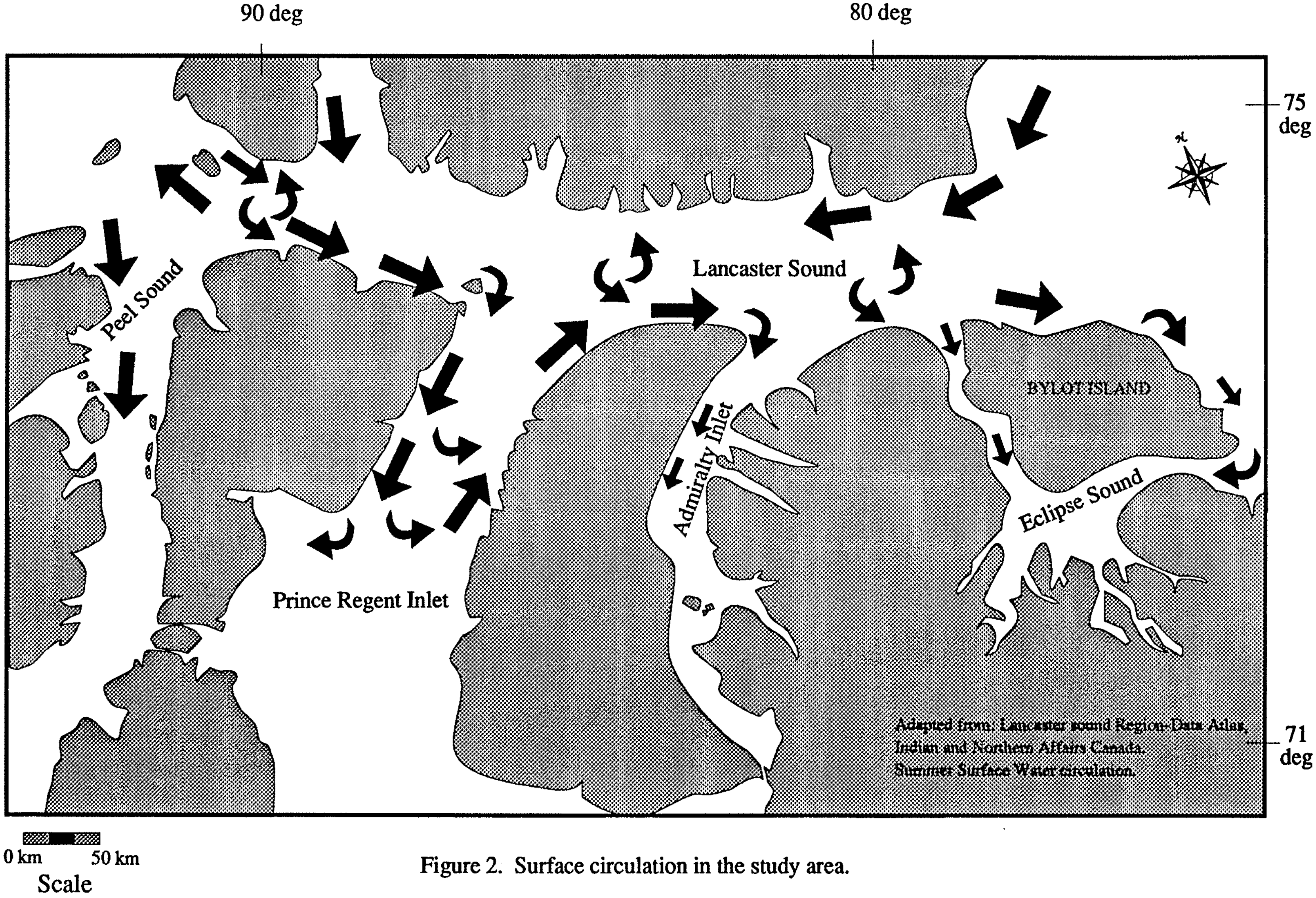
[1] FLIR is a registered trademark of FLIR Systems Inc.



Adapted from: Lancaster sound Region-Data Atlas, Indian and Northern Affairs Canada. Summer Surface Water circulation.

Figure 2. Surface circulation in the study area.

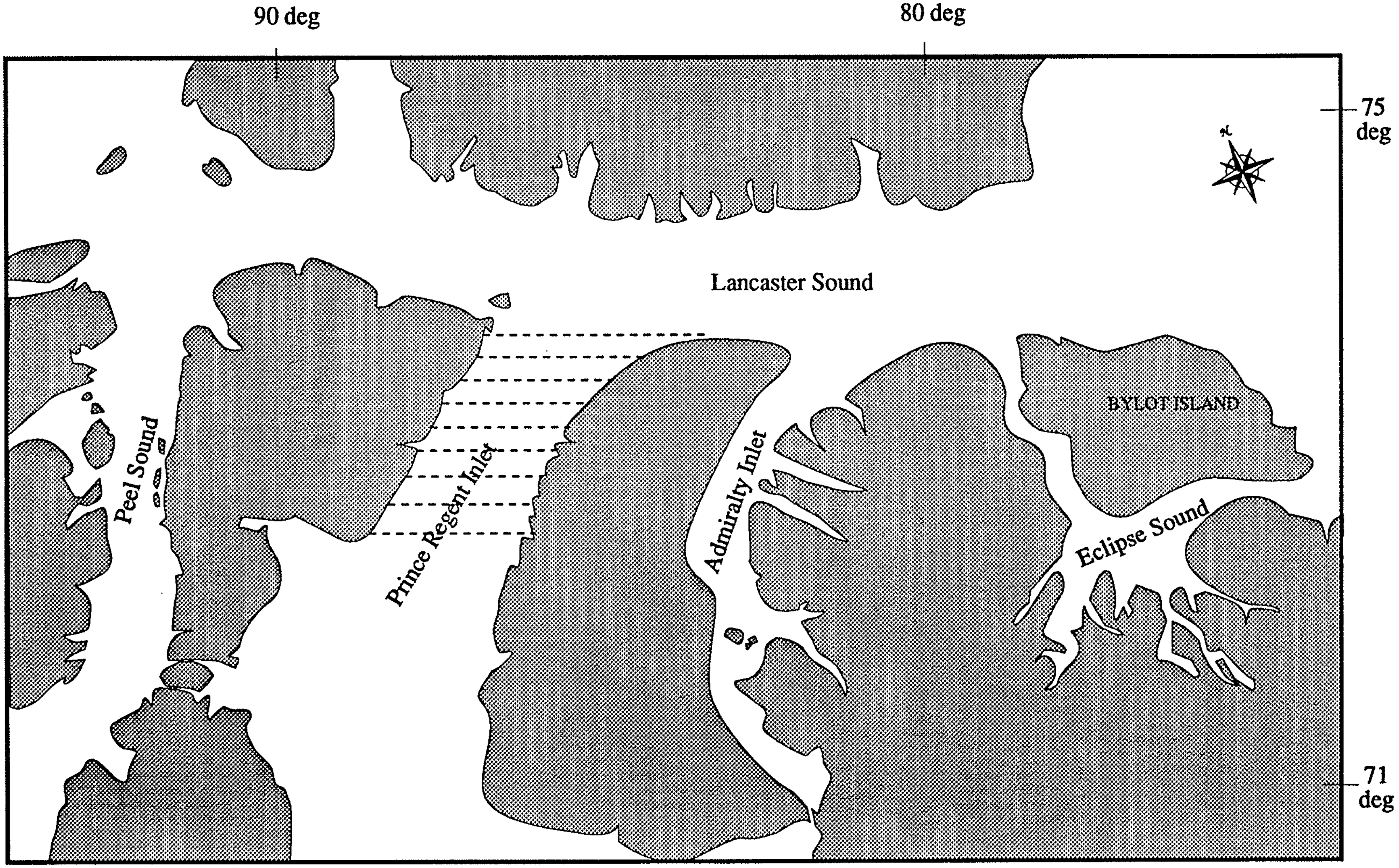


Figure 3. Transect data used in 1984.

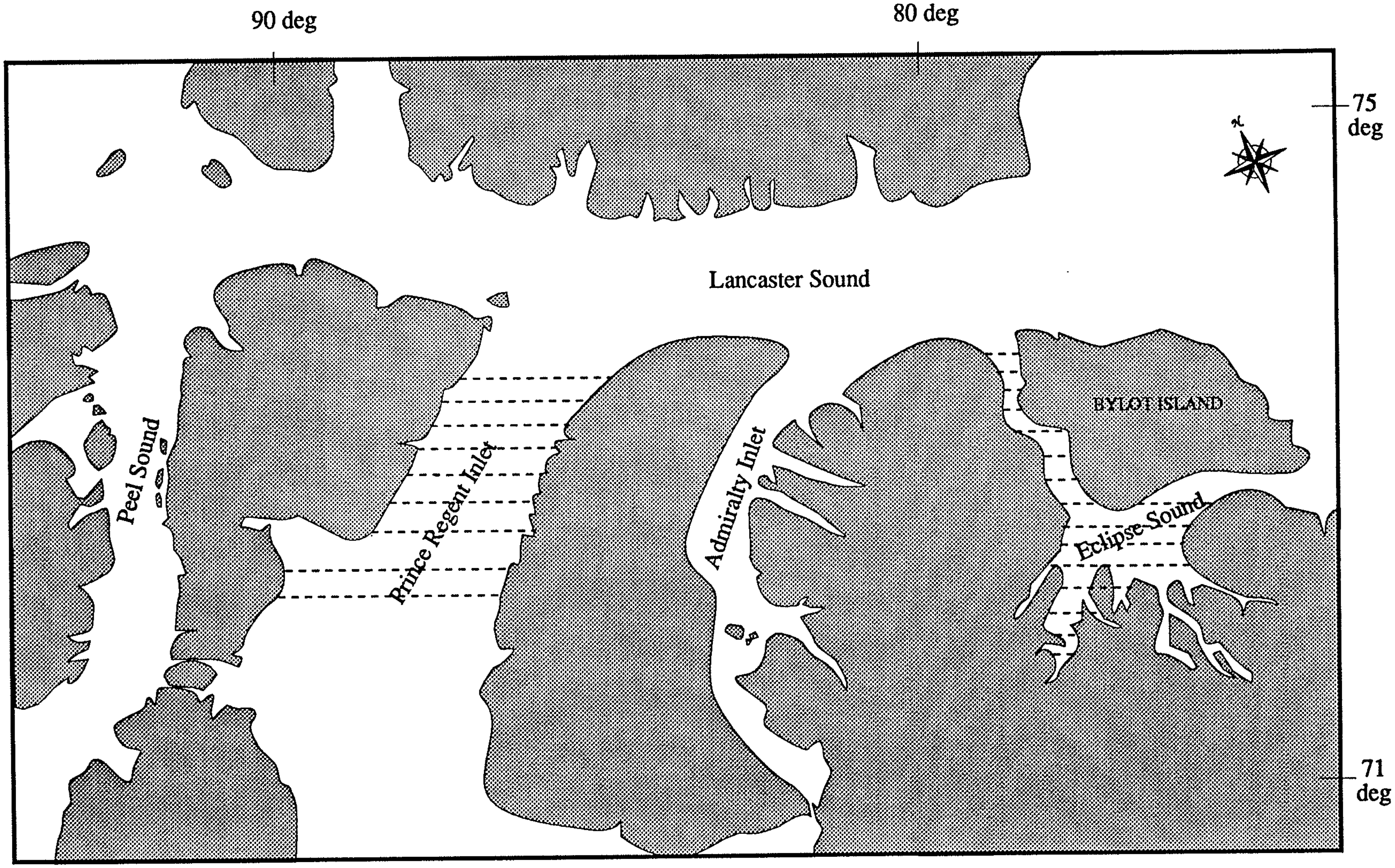


Figure 4. Transect data used in 1985.

Interpretation of the aerial film was divided into individual sessions of fifteen photo frames. Mean interpretation time per session was 1.25 hrs. A maximum of 4 sessions per day was implemented to reduce potential errors in image interpretation due to boredom and fatigue. Each photograph was viewed with a Nikon SMZ-1 microscope mounted on a Richards GFL-940MC light table. A 228.6 mm by 228.6 mm grid, divided into nine segments, was used to locate whales in each photograph.

Six maturity or sex classes were discriminated on the aerial photographs: tusked adults (assumed to be male; Finley and Gibb 1982), non tusked adults (assumed to be female), adults accompanied by a calf or juvenile (assumed to be cows), calves, juveniles, and an unknown class. Adults appeared mottled black and white, and approximately 8 mm long (image length). Calves were light coloured (negative film) and one third the size of the cow they accompanied. Juveniles were also light coloured and two thirds the size of the accompanying adult. The size distinction of juveniles may lead to some ambiguity in this class because of the wide range of cow lengths. Images that were detected and identified as narwhal, but could not initially be distinguished into a maturity class or sex class were denoted as unknown and reviewed by the photo interpreter. If an image was initially identified as narwhal and identification of maturity class or sex class was not determined on the second viewing, the observation was classed as an adult. Images not identified as narwhal were also classed as unknown and were reviewed by two photo interpreters. An image within the same photograph as identified narwhal was classed as adult. Images detected but not identified to species and not located in the same photograph as positively identified narwhal, remained in the unknown class and were not considered in this investigation.

2.22 FLIR imagery

The Forward Looking Infrared (FLIR) thermal imager provided information on the location of thermal boundaries. The imager is sensitive to emitted thermal infrared radiation at a peak wavelength of 10.6 μm. The horizontal field of view is 28°; the vertical field of view 17°; the instantaneous field of view (IFOV) is 1.87 mrad; and the effective focal length is 2.71 cm. Temperature differences as small as 0.15 °C can be detected. Incident thermal radiation is recorded as a continuous analogue signal and output to a video cassette recorder. The on-board FLIR display monitor provides 10 grey shades of radiometric resolution. Details pertaining to thermal remote sensing with the FLIR are presented in Appendix C.

The FLIR was located in the nose cone of the Twin Otter. The sensor was depressed approximately 30° from horizontal. In this configuration, the FLIR imaged the ocean surface approximately 1583 meters in front of the aircraft [1], at a swath (perpendicular to transect orientation) of 912 m [2].

$$\text{Tan } 60^{\circ} \text{ X } 914.4 \text{ m} = 1583.8 \text{ m} \qquad [1]$$

$$\text{Swath width} = 2\left(\text{TAN } 14^{\circ}\left(\frac{A}{\text{COS } 60^{\circ}}\right)\right) \qquad [2]$$

Where: A is the flying altitude (914.4 m).

The image area recorded by the FLIR was keystone shaped, with the narrow part of the keystone closer to the aircraft. The 912 m swath is calculated at the scale of the principal point of the oblique image (i.e., the scale at one half the vertical field of view). FLIR data were viewed using a JVC video cassette recorder (VCR), model HR-D151U and a high resolution monochrome Panasonic video monitor. A grid, overlaid on the video monitor, was used to ensure boundary positions were recorded consistently (Fig. 5). When a boundary passed into the target zone, the tape count was recorded. Boundaries were recorded as prominent (large grey level difference across the boundary) and not prominent (small grey level difference across the boundary). Only three prominent boundaries were observed, each in 1984. Prominent boundaries were accompanied by small, local fog patches directly over the boundary.

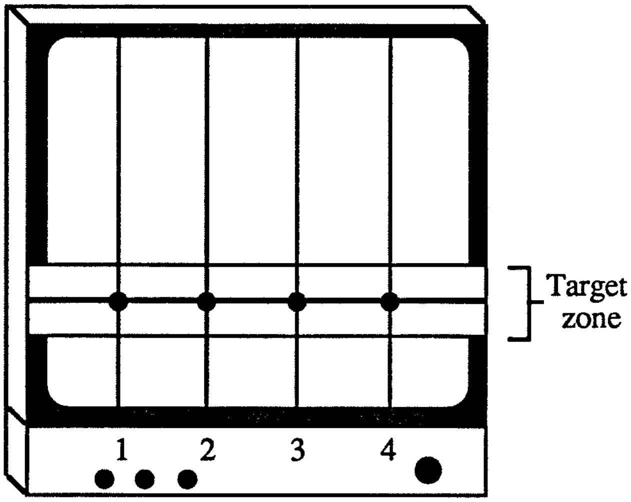


Fig. 5. Schematic of grid overlay used to define target area.

2.23 Matching the FLIR and photographic records

To enable comparison between FLIR records and aerial photography, each was coded to time from beginning of the transect. Frame centres (F_i) were used to locate narwhal (in units of time) from the centre of the first photograph on each transect (F_b). All narwhal in a particular photo frame (F_i) were located at time (T_i) regardless of where they were located in the photograph. If the camera was stopped because of fog or land, the frame location was adjusted from the beginning of the transect. The equation used to convert frame number to location from beginning of the transect is provided in [3].

$$((F_i - F_b) + 1) \times T_i = \text{Location (in decimal minutes)} \qquad [3]$$

Where:

F_i = Frame containing narwhal.

F_b = First photograph of the transect.

T_i = Camera interval (S) ÷ sixty seconds.

The location of thermal water mass boundaries also was coded to time. Boundary locations were recorded by tape count obtained from the VCR. The VCR counter increments with each revolution of the take-up spool. These tape counts displayed a curvilinear relationship with elapsed time because the counter recorded the speed at which the take-up spool rotated. One VCR tape was sampled every 200 increments of tape count, throughout the entire duration of a 2 hour tape. The amount of time that elapsed during the 200 count was recorded. A polynomial equation [4] was computed based on these samples. Appendix A provides further detail on the relationship between time and tape-count.

$$\hat{Y}_i = -0.1354 + 1.3507\, X_i + 0.0338\, X^2_i \qquad [4]$$

Where: $\hat{Y}_i$ is the predicted time value
X_i is the observed tape count

To evaluate the consistency between photographic and FLIR records, transect total lengths were compared between the two data sets. The difference in total length (in decimal minutes) was computed for each transect. The mean difference and standard deviation were 0.42 min and 0.06 min. This translates into an error slightly larger than one photograph in distance (~0.3667 min at an interval of 22 s). Since the limit of spatial precision in locating narwhal is the size of one photo frame (distance between adjacent frame centres) the discrepancy between FLIR and photographic records was slightly larger than the precision of narwhal location.

2.3 Data Analysis

Data analyses were conducted on those transects for which concurrent FLIR and photography were available. Methods for each of the research questions (section 1.3) are presented below. Specific details of the statistical analyses employed are located in Appendix D, and in the statistical reference citations.

2.31 Question one

To determine if a significant correlation exists between the location of thermal boundaries and narwhal, each was reduced to a binary variable of presence and absence. A chi-square test was used to determine if the co-occurrence of narwhal and thermal boundaries was significantly different from that expected under the hypothesis of independence. Sample area is an important factor in measurement of correlation amongst species and between species and habitat (Pielou 1969; Rougharden 1977; and Porter and Church 1987). To incorporate known errors in positional accuracy between the FLIR and photography and to ensure that these discrepancies do not affect testing significance, two sampling intervals were used. For each transect where both thermal boundaries and narwhal were identified the transect was separated into spatial units equivalent to one RC8 frame (22 s ÷ 60 s = 0.367 min) and into two RC8 frames (0.733 minutes) in time. This resulted in sample units of approximately 1372 m by 1372 m and 2744 m by 1372 m, of ocean surface. The number of sample units per transect depended on transect length. All pairwise combinations of the binary variable (presence - absence) for thermal boundaries and narwhal, were tabulated for each transect and used to compute the chi-square statistic [5]. The test hypotheses were:

- H_O = Narwhal and thermal boundary locations are independent.
- H_a = Narwhal and thermal boundary locations are not independent.

$$\chi^2 = \sum_{i=1}^{4} \frac{(O - E)^2}{E} \qquad [5]$$

Where;

O = Observed value of each cell in the chi-square matrix.

E = Expected value under the null hypothesis (see Appendix D.).

To obtain an ordinal measure of correlation between narwhal and thermal boundaries the Q statistic was used (Pielou 1969). This statistic tests whether lack of independence, determined from a chi-square test can be attributed to a negative or positive spatial correlation. The statistic also provides a means of comparing the strength of correlations between years. Computation of the Q-statistic and variance term, are presented in Appendix D.

2.32 Question two

A bivariate test was conducted to determine the utility of thermal boundaries for stratification of survey designs. Variable 'NB' is the minimum distance between narwhal presence (binary variable of presence-absence) and the nearest thermal boundary. The minimum distance was calculated parallel to transect orientation. A surrogate variable ('UB') consists of the distance between points uniformly distributed along the transect line and the nearest thermal boundary. The uniform points were spaced at an interval of 0.367 min. The resulting distribution of 'UB' indicates the frequency of distances that would occur if narwhal were uniformly distributed within the sample. Variable 'NB' indicates the frequency of distances that occur given the observed distribution of thermal boundaries. Because both variable 'NB' and 'UB' use the same thermal boundary locations, if variable 'NB' consists of a higher frequency of shorter distances than variable 'UB' we can conclude that thermal boundaries would be a useful stratification variable. This result would of course be limited by the sample of thermal boundary and narwhal locations.

A Kolmogorov-Smirnov two sample test (Sokal and Rohlf 1981) was employed to determine if variables 'NB' and 'UB' are significantly different. A non parametric approach was selected because both variables violate the assumption of normality required for an equivalent parametric test. The test statistic is described in Appendix D. The test hypotheses were:

- H_o = Variable 'NB' and variable 'UB' come from the same distribution.
- H_a = Variable 'NB' and variable 'UB' are not from the parent distribution.

2.33 Question three

Analysis of the relationship of specific maturity classes or sex classes in relation to thermal boundaries was conducted using the same methods as question two. For the purpose of this analysis, the classes tusked and cow/calf pairs were considered an unbiased estimate (Mendenhall et al. 1971) of the true proportion of tusked and cow-calf pairs in the population. The minimum distances between tusked narwhal and the nearest thermal boundary and from cow-calf pairs to the nearest thermal boundary were calculated. To determine whether maturity class or sex class location is a function of the minimum distance to a thermal boundary the distribution of distances (to boundaries) for each were compared. The Kolmogorov-Smirnov test was used; comparison of means indicates which distribution consists of shorter distances. The test hypotheses were:

- H_o = The tusked and cow-calf pair distributions of minimum distances to thermal boundaries come from the same distribution.
- H_a = The tusked and cow-calf pair distributions of minimum distances to thermal boundaries are not from the same distribution.

2.34 Question four

A one way ANOVA was used to determine if a higher density of narwhal locate closer to thermal boundaries. Narwhal densities were calculated according to [6].

$$\hat{D} = n_i \div A \qquad [6]$$

Where: $\hat{D}$ = narwhal density
n_i = number of narwhal per frame
A = photo frame area (1.372 km^2)

To obtain relatively equal sample sizes the frequency of distances were separated in two groups. Group 1 consisted of the density of narwhal less than 0.367 min (one photo frame) distant from the nearest thermal boundary. Group 2 consisted of densities at distances greater than 0.367 min. Bartlett's test (Sokal and Rohlf 1981) was conducted to assess homogeneity of the variances between the two groups. This test resulted in the conclusion that the variances were heteroscedastic, therefore a $\log_{10}$ (1+X) transform was applied. The transformed variables were found to be acceptably homoscedastic. The test hypothesis were:

- H_0 = Densities less than 0.367 min from a thermal boundary are equal to densities at distances greater than 0.367 min.
- H_a = Densities less than 0.367 min from a thermal boundary are not equal to densities at distances greater than 0.367 min.

2.35 Narwhal distribution relative to shore

The minimum distance between narwhal presence and shore was calculated for 1984 and 1985. These distances were measured from all photo frame centres with narwhal present to the nearest shore, regardless if thermal data were available. Small islands were not considered shore. The resulting frequency distributions illustrate how narwhal were distributed within the sample relative to shore in 1984 and 1985. The data, when contrasted with historical information on how narwhal distribute relative to shore, provides information useful for interpretation of results between the 1984 and 1985 survey years.

CHAPTER 3.0: RESULTS

3.1 Question one

In 1984 the co-occurrence of narwhal and thermal boundaries was observed more often than would be expected under the hypothesis of independence at a sample spacing interval of 0.367 min (Table 1). No significant correlation was observed in 1985. Increasing the sample interval spacing to 0.733 minutes resulted in a marginal increase in the Q statistic (0.566 to 0.568; Table 1). With a corresponding increase in variance from 0.0065 to 0.0112 the change was not significant (Table 1). In 1985 the 0.367 min sample interval resulted in a non-significant chi-square and a Q statistic near zero (0.053; Table 1). The 0.733 min interval provided no improvement in either statistic (Table 1).

Table 1. Results of the chi-square test and Q statistic measure of correlation.

Date	Sample interval	χ^2 Calc[1].	χ^2 Crit[2].	Significance	Q stat.	Q var.
1984	0.367 min.	32.86	7.88	0.005	0.566	0.0065
	0.733 min.	17.87	7.88	0.005	0.568	0.0112
1985	0.367 min.	0.053	7.88	NS[3]	0.053	0.033
	0.733 min.	0.063	7.88	NS	NS	NS

---

[1] χ^2 Calc = Calculated chi-square value from [5].

[2] χ^2 Crit = Critical value from the chi-square distribution at α=0.005 and df=1

[3] NS = Not Significant

3.2 Question two

The distances between narwhal and thermal boundaries ('NB') and between uniformly distributed points and thermal boundaries ('UB') resulted in the following two frequency distributions (Figs. 6 and 7).

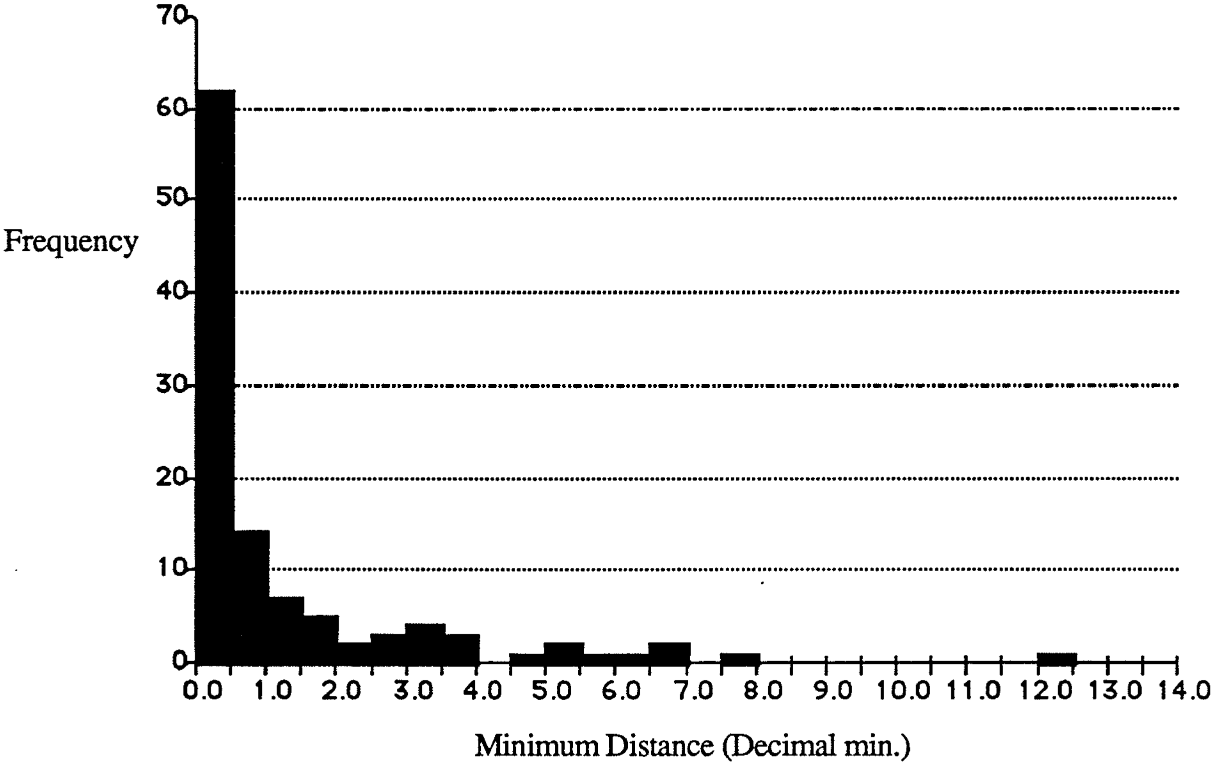


Fig. 6. Variable 'NB'; minimum distance between narwhal and thermal boundaries in 1984.

Variable 'NB', in 1984 has a mean of 1.19 min, a standard deviation of 2.04 min, and a sample size of 109. N is the number of photographs with one or more narwhal present. Minimum distance is between narwhal presence and the nearest thermal boundary.

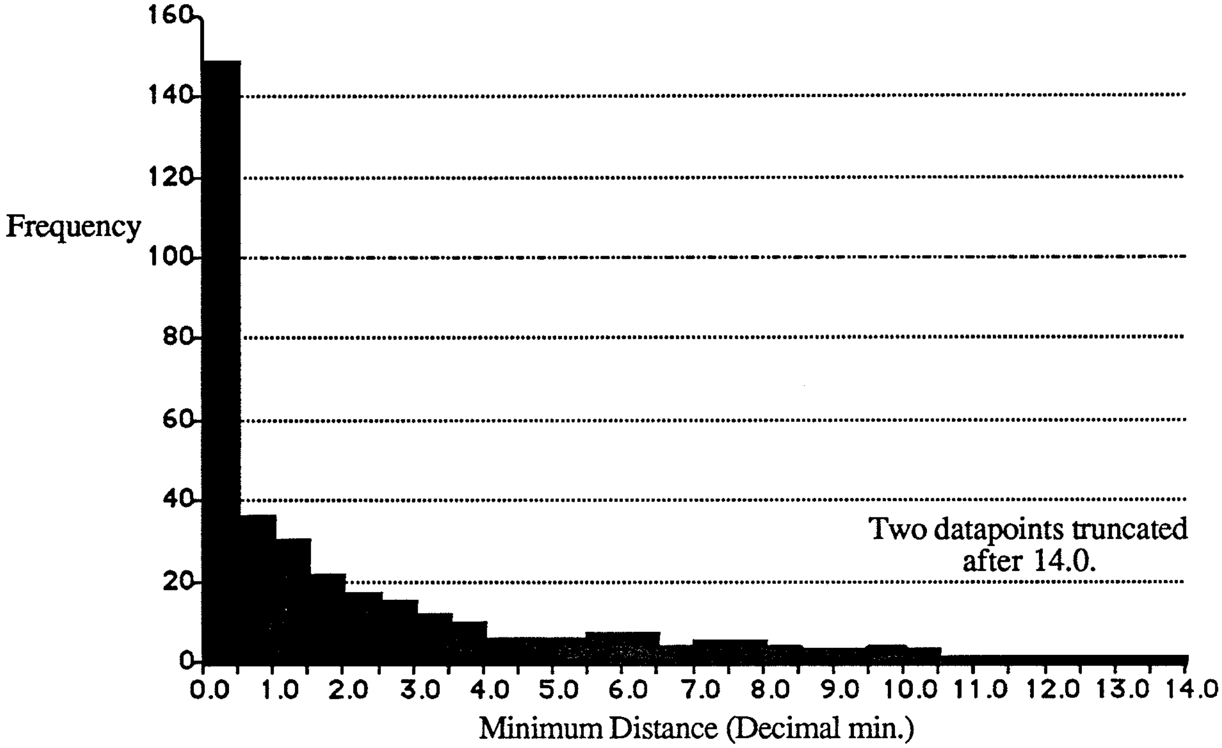


Fig. 7. Variable 'UB'; minimum distance between uniform points and thermal boundaries in 1984.

Variable 'UB', in 1984 has a mean of 2.44 min. a standard deviation of 3.40 min. and a sample size of 368. In this variable, N is the total number of points uniformly spaced at 0.367 min for all transects where concurrent FLIR imagery was available.

It is apparent from figure 6 and 7 that variable 'NB' and variable 'UB' are different. Test of the 1984 data resulted in a significant Kolmogorov-Smirnov statistic; $D_{max} = 0.22 > D_{0.01} = 0.18$; therefore reject the null hypothesis that these distributions are samples from the same population.

The distributions of minimum distances for variables 'NB' and 'UB' were also computed for the 1985 data (Figs. 8 and 9).

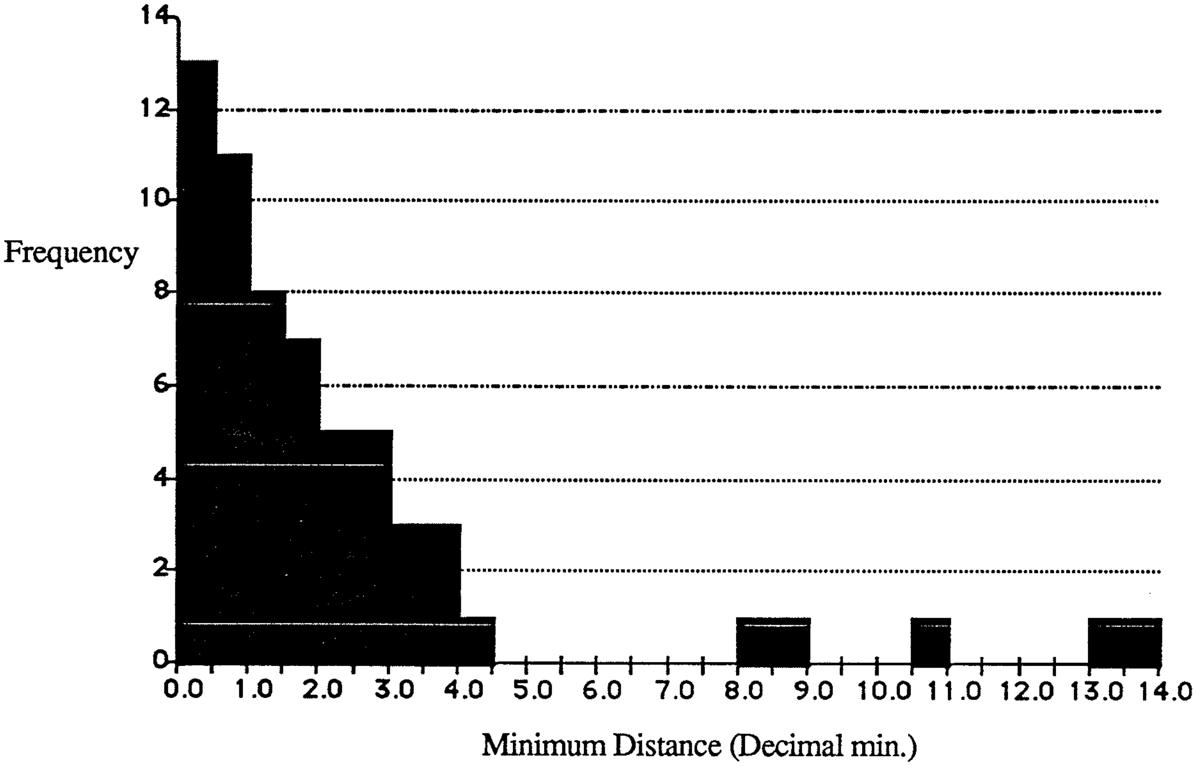


Fig. 8. Variable 'NB'; minimum distance between narwhal and thermal boundaries in 1985.

Variable 'NB' in 1985, has a mean of 2.26, standard deviation of 2.88, and a sample size of 61.

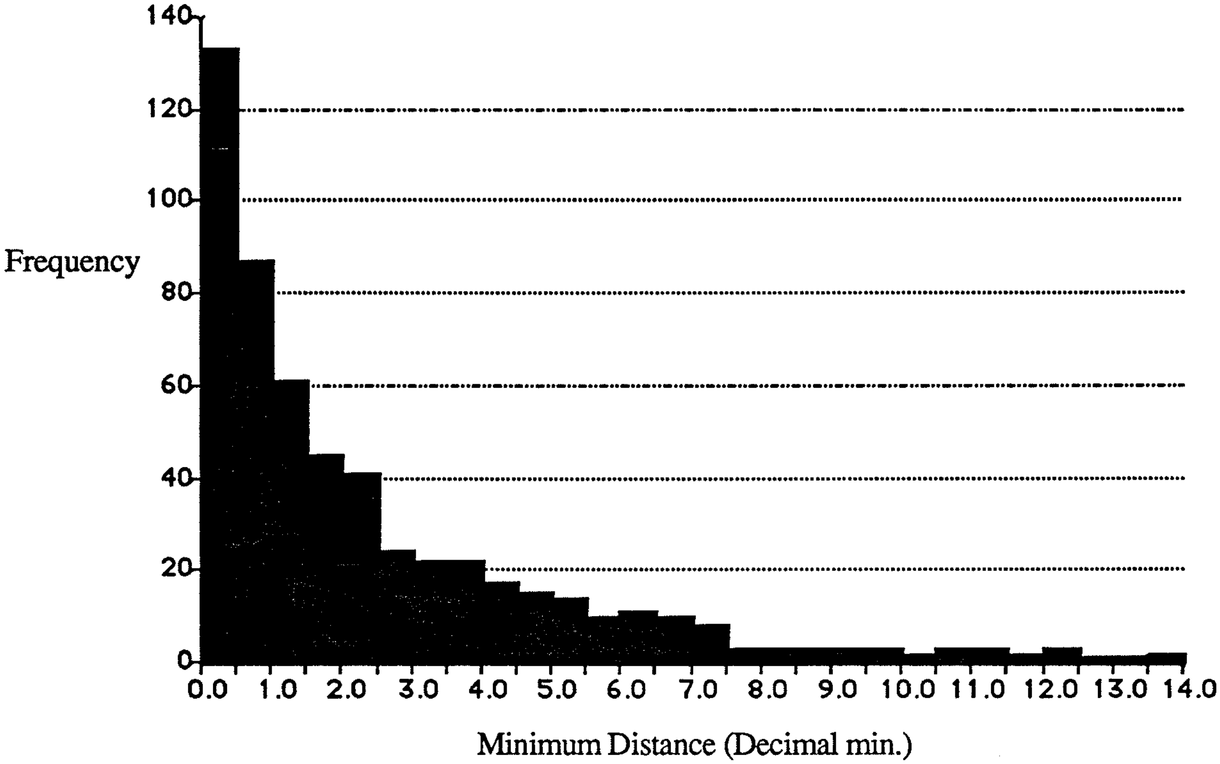


Fig. 9. Variable 'UB'; minimum distance between uniform points and thermal boundaries in 1985.

Variable 'UB' in 1985 has a mean of 2.46, standard deviation of 2.72, and a sample size of 552. The average minimum distance is larger between narwhal and thermal boundaries than between uniform points and thermal boundaries. Test of the 1985 data resulted in a non-significant Kolmogorov-Smirnov statistic; $D_{max} = 0.126 < D_{0.2} = 0.145$; therefore conclude these distributions are samples from the same population.

3.3 Question three

The frequency distribution of distances between tusked and cow-calf pairs to the nearest thermal boundaries are provided in Figure 10 and 11. Analysis of maturity class-sex preference for thermal boundaries is conducted only on the 1984 data because the co-occurrence of narwhal and thermal boundaries in 1985 was not significant.

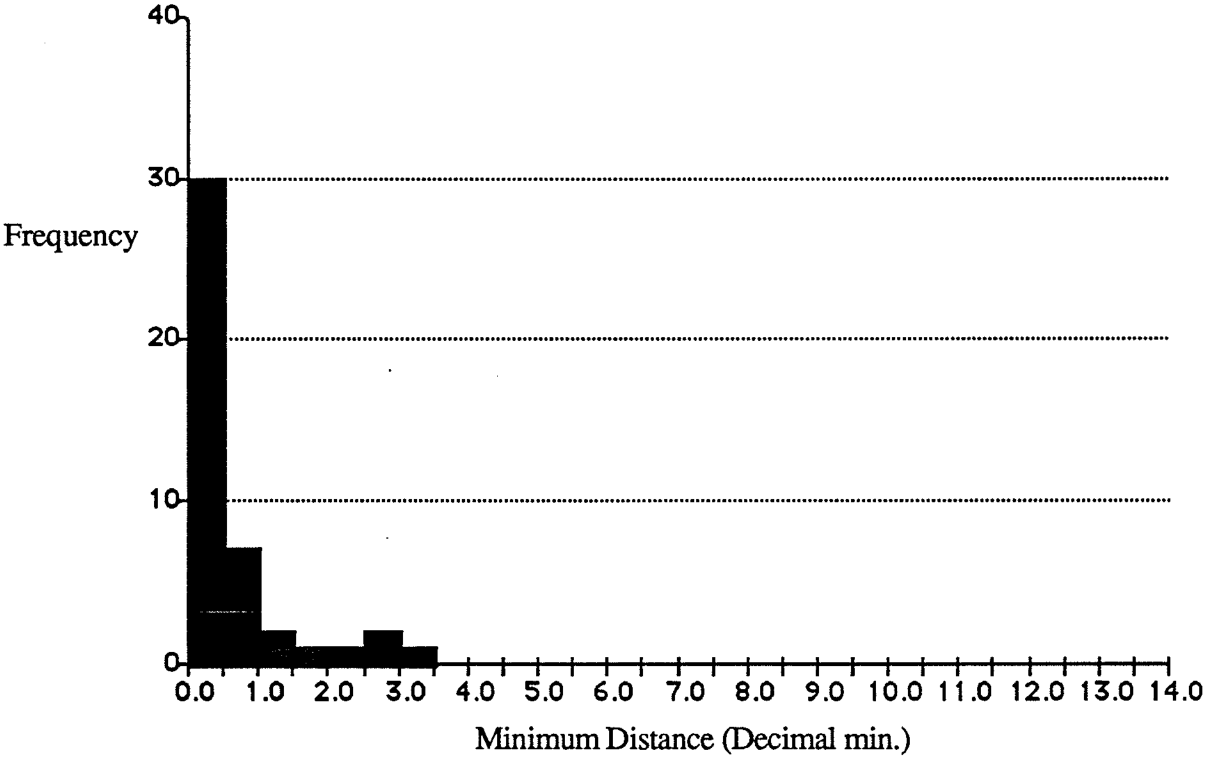


Fig. 10. Minimum distance between cow-calf pairs and the nearest thermal boundaries in 1984.

The cow-calf pair distribution of minimum distances to thermal boundaries has a mean of 0.51, standard deviation of 0.83, and a sample size of 44.

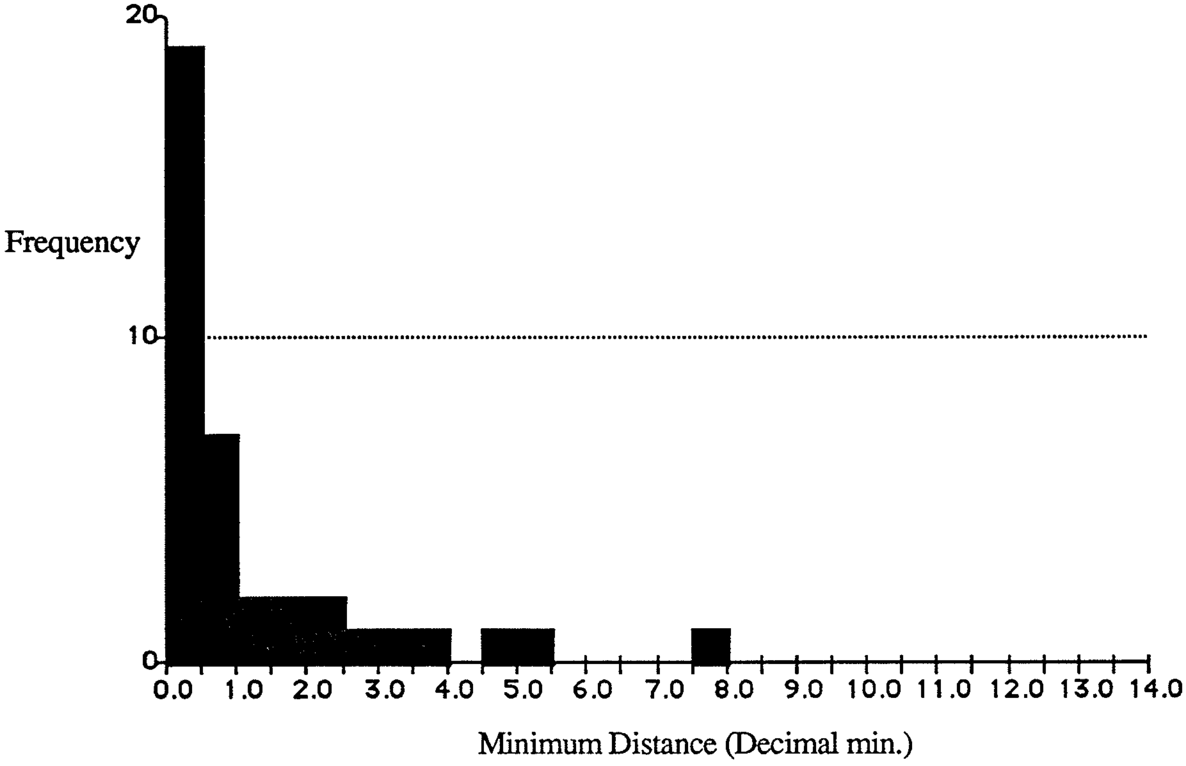


Fig. 11. Minimum distance between tusked narwhal and the nearest thermal boundaries in 1984.

The tusked distribution of minimum distances to thermal boundaries has a mean of 1.13, standard deviation of 1.76, and a sample size of 38.

Comparison of these distributions resulted in a non-significant Kolmogorov-Smirnov statistic; $D_{max} = 0.11 < D_{0.1} = 0.27$; therefore conclude these distributions are samples from the same population.

3.4 Question four

The relationship between narwhal density and distance to the nearest thermal boundary (Fig. 12) shows a trend for a higher frequency of shorter distances (more points towards zero on the X axis). These data also suggest that a larger frequency of whales per photograph are observed at shorter minimum distances to thermal boundaries (increase on Y at small X values).

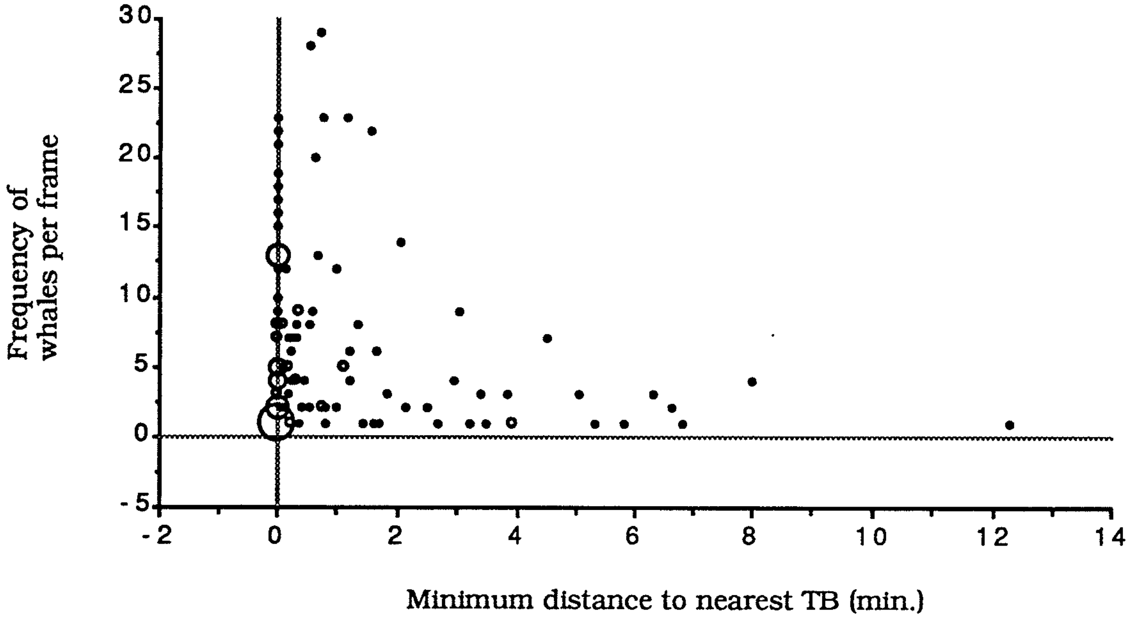


Fig. 12. Frequency of animals at different minimum distances to thermal boundaries.

A one way analysis of variance (ANOVA) was calculated for the 1984 data, on the density of animals less than 0.367 min from a boundary, and at distances greater than 0.367 min. Data were transformed to obtain acceptable homoscedasticity for conducting a parametric analysis of variance. The transformed data show a larger mean for the shorter distance category (Table 2).

Table 2. Transformed (log10 (1+x)) data.

Category range (min.)	Mean	Std. dev.	Std. Error	Count
0 min. ≤ G1 < 0.367	0.698	0.3	0.039	60
0.367 > G2 ≤ 12.280	0.049	0.345	0.595	49

Results of the ANOVA confirm that this larger mean is significantly different than the mean of category 2. The F statistic is significant at the 90 percent level (Table 3).

Table 3. ANOVA for the abundance of animals relative to minimum distance from thermal boundaries.

Source:	DF:	Sum Squares:	Mean Square:	F-test:
Between	1	0.289	0.289	2.805
Within	107	11.007	0.103	p =.0969
Total	108	11.296		

3.5 Narwhal distribution relative to shore

Differences observed in the results to research questions one through four, should be evaluated in light of between year differences in narwhal distribution. The minimum distance between narwhal presence and the nearest shore show that animals were located further from shore in 1984.

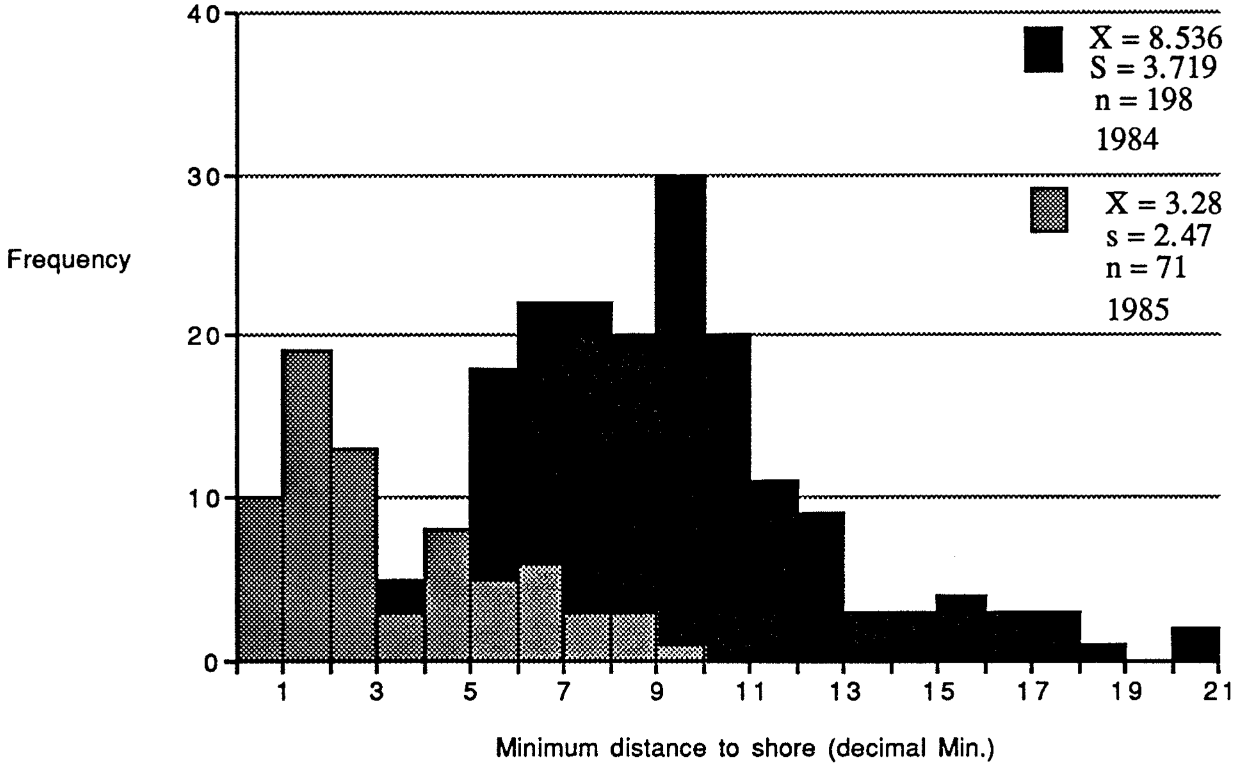


Fig. 13. Minimum distances from narwhal to shore, 1984 and 1985.

The Kolmogorov-Smirnov test confirms what is graphically obvious ($D_{max} = 0.41 > D_{0.01} = 0.225$); therefore conclude that narwhal were significantly closer to shore in the 1985 sample.

CHAPTER 4.0: DISCUSSION

Results of the chi-square analysis indicate that narwhal and thermal boundaries co-occurred, more often than would be expected by chance in 1984 but not in 1985. This discrepancy between the two years is indicative of the complexity of narwhal - habitat relationships and meant that analysis of the more detailed relationships between narwhal and thermal boundaries (research questions three and four) was restricted to the 1984 data. Factors occurred in 1985 which caused the differences observed. Determining what these factors are and over what time scale they occur is a logical progression of this work. There is insufficient evidence to conclude that narwhal prefer to locate near thermal boundaries consistently enough to consider this preferred habitat. The only conclusion available is that narwhal and thermal boundaries did co-occur in 1984. Whether this relationship is sufficiently consistent to be useful for management purposes must be considered in future research.

Analysis of the frequency of minimum distances between narwhal and thermal boundaries ('NB') in 1984 consists of significantly shorter distances than we would expect given a uniform distribution of narwhal ('UB'). To help rationalize the differences in how the distributions 'UB' and 'NB' relate to sample collection, consider 'UB' as the result of a systematic transect and 'NB' a sample stratified on the location of thermal boundaries. The shorter mean distance between narwhal and thermal boundaries ('NB') means that the stratified approach would be more efficient, since more narwhal are located close to boundaries than at larger distances. This result is encouraging but must be considered further to clarify the conditions under which we can expect a similar result. This is a necessary prerequisite to the operational use of this information.

From a behavioural viewpoint it is interesting to consider whether certain maturity classes or sex classes prefer to locate differently relative to thermal boundaries. Significant differences may provide insights into possible reasons for preference by narwhal for boundaries. Results of this analysis showed there was no evidence to conclude that tusked narwhal or cow-calf pairs preferred to locate differently relative to thermal boundaries. This suggests that the behaviour related to why narwhal located near thermal boundaries in 1984 is common to both tusked narwhal and cow/calf pairs.

The analysis of whether narwhal density is higher closer to thermal boundaries is an important consideration in the design of future narwhal surveys. This analysis indicates that density is greater within 0.367 min of thermal boundaries than at larger distances. Since the samples were of unequal size and the mean difference was significant only at the 90 percent level the result indicates a possible relationship, not a conclusive one. A sample obtained at a thermal boundary may be biased if the behaviour of animals is different at the boundary than elsewhere. It is important to clarify the characteristics of this bias if thermal boundaries are to be used as a stratification variable or when interpreting systematic survey results.

Analysis of the distribution of narwhal in the study area shows that narwhal were distributed differently in the two years. Since the 1984 distribution is more typical of narwhal (section 1.22) consideration must be given to why the high frequency of small distances to shore were observed in 1985. One possible cause is the presence of a natural predator of the narwhal; the killer whale (*Orcinus orca*). It has been suggested elsewhere (Steltner et al.1984; Finley and Davis 1984) that narwhal avoid killer whales by seeking refuge in shallow waters close to shore. During the course of the surveys by Strong et al. (unpubl. data) killer whales were observed both in Admiralty Inlet and Eclipse Sound. DFO personnel observed a group of 8 or 9 killer whales in Admiralty Inlet on 16 August, 1985. Narwhal were observed very close to shore simultaneous to the killer whale observations (Larry Dueck. Dept. of Fisheries and Oceans, 501 University Cres. Winnipeg, MB. pers. comm.). Killer whales were also observed on numerous occasions during August 1985 in Eclipse Sound, by research personnel and Inuit hunters (Campbell et al. 1988). Campbell et al. (1988) observed that narwhal avoided these killer whales by moving into shallow water close to shore. Although these groups conducted the same research activities in the summering areas in 1984 no killer whales were sighted.

This observation is convenient and may in fact be the significant factor which created the unusual distribution in 1985. Unfortunately there is insufficient evidence for a conclusive statement. The behaviour of narwhal both within and between the summering areas is so poorly understood that attributing the lack of correlation in 1985 to the presence of killer whales would be premature. The temporal resolution of the data (in both years) consists of a 1/250 s in time for an individual observation (shutter speed) and at most a 5 hour time frame (one survey flight) for a single geographic location within the summering areas.

Periodic fluctuations in distribution could easily exist within this very limited time frame.

Results of this research are complicated by the lack of agreement between the two survey years. If 1985 data had provided a similar relationship to 1984, conclusions would have remained the same. The consistency of this relationship cannot be ascertained using data with a temporal resolution of fractions of a second. Repetitive coverage of a smaller geographic location is required.

The results show that a relationship existed between narwhal and thermal boundary locations at the time of sample collection in 1984. The 1985 results show that the universality and variability of this co-occurrence over time and space are unknown. Conclusions based on these results must be interpreted in light of these limitations and future research should be designed to investigate this phenomenon further.

CHAPTER 5.0: CONCLUSIONS

Narwhal preferred to locate near thermal boundaries in 1984 but not in 1985. The lack of correlation in 1985 indicates that other factors affect the universality and consistency of the results observed in 1984. Specific conclusions include:

- Co-occurrence of narwhal and thermal boundaries was higher than expected by chance in the 1984 sample but not in 1985.

- Minimum distances between narwhal and thermal boundaries indicate that stratification would be effective based on the 1984 sample.
- There is no evidence to suggest a sex class or maturity class preference for boundaries.
- Density dependence on proximity to thermal boundaries was indicated but is not considered conclusive.

Interpretation of the differences between 1984 and 1985 should be interpreted in light of the distributional differences evidenced in each year. Narwhal were distributed in a traditional manner in 1984 and were significantly closer to shore in 1985.

5.1 Limitations

The first limitation of this research is the lack of repetitive observations of narwhal and thermal boundary locations over time. Since the data were obtained concurrent with the abundance survey program (Strong et al. unpubl. data) there was no opportunity for repetitive coverage. A second limitation is the lack of information on sea surface temperatures between transects. The analysis presented here consists of the correlation between location of thermal boundaries and narwhal on each transect. If a transect passed along the side of a thermal boundary narwhal may be present but no thermal boundary evident. This limitation could be addressed by using the National Oceanographic and Atmospheric Administration (NOAA) meteorological satellite.

Unfortunately sufficient NOAA imagery was not available for this study because of complications in data archival. A final limitation is a lack of information on why narwhal use each of the summering areas, and whether they use different areas for different reasons. This problem needs to be addressed before a longitudinal study of a smaller geographic area is conducted.

5.2 Management Implications.

Because of the discrepancy between years, results relating to the primary objective of this study remain inconclusive. There are however specific items which can provide information for management of narwhal in the study area.

- Throughout this analysis the sample of narwhal and thermal boundary locations was assumed an unbiased estimate of their true population parameters. Narwhal behaviour may result in a biased estimate of both density and relative frequency of the binary variable (presence-absence), used throughout these analyses. Knowledge of narwhal behaviour relative to habitat preference is an important parameter in survey precision. If the proportion of animals represented in a sample change with behaviour, it is important to understand and be able to identify areas where this change will occur.

- If the results of the 1984 analyses are considered indicative of the true relationship between narwhal and thermal boundaries then survey precision would be enhanced by stratification on thermal boundaries. The results based on 1985 data suggest that other factors relating to behaviour affect the constancy of the narwhal-thermal boundary relationship. Narwhal behaviour both within and between the summering areas must be studied to determine the frequency of the results observed in 1985.

- Because of the physical mechanics of fronts and upwellings these locations are collection sites for surface debris and pollutants (Laevastu and Hayes 1981). The location of prominent fronts and upwellings move with changes in tide, current and meteorological conditions. Re-occurrence of these features in a particular location could be inferred through measurement of these conditions. If narwhal prefer to locate at these fronts the probability of animals contacting surface borne pollutants is high.

5.3 Recommendations.

A more detailed study is necessary to confirm or deny the results presented here. These results do however warrant conducting a longitudinal study in a smaller geographic area. This study should be conducted in conjunction with broad coverage abundance surveys. The local area data would be used to assess the relationship between thermal boundary and narwhal location over time. The broad coverage data would be used to address differences in the narwhal-thermal boundary relationship between summering areas. Other factors affecting the relationship between narwhal and thermal boundaries could be identified and factored into the model for this relationship.

Recommendations, specific to management implications (section 5.2), can be conducted either in concert with, or independent of, a longitudinal study.

- The narwhal deep diving behaviour, indicative of feeding, can be inferred from aerial photographs by presence of dive pools and partial body images (Barber and Hochheim 1987). Aerial film should be reviewed to measure group size, orientation, identification of dive pools, and a measure of the proportion of whole body images to partial body images. Partial body images are indicative of surfacing or diving (water clarity held constant). This information would assist in clarification of whether the higher frequency of animals at thermal boundaries is unbiased or whether there is evidence of behavioural changes as a function of distance from thermal boundaries.

- Preliminary work to determine the statistical advantage (increased precision) of using thermal boundaries as a stratification variable could be conducted using the 1984 data. Factors affecting this relationship are tied to our lack of understanding of basic narwhal behaviour. Tagging programs designed to investigate narwhal behaviour could be coupled with a longitudinal study of the relationship between narwhal and thermal boundaries.

- Document the location of thermal boundaries using thermal wavelength satellite imagery in the open water season on a daily basis or as often as cloud free images can be obtained. Couple this analysis with microclimatological conditions in the study area to develop a basic understanding of the conditions under which upwelling and frontal activity occur. Knowledge of the location and repeat occurrence of these features would be useful in the event of an oil or chemical spill in the Arctic marine environment. The information would also be useful in differentiating oceanographic conditions between each of the summering areas, illuminating the question of whether narwhal use different summering areas for different reasons.

The results of this investigation provide the first evidence that narwhal prefer to locate near thermal boundaries. It is also apparent that this relationship is affected by other factors, which at this time remain unknown. Several important questions have evolved from this analysis and can provide the basis for a more detailed study of the narwhal-thermal boundary relationship. This study provides only a single link in the chain of information necessary to understand the complex relationships that exist between narwhal and their habitat.

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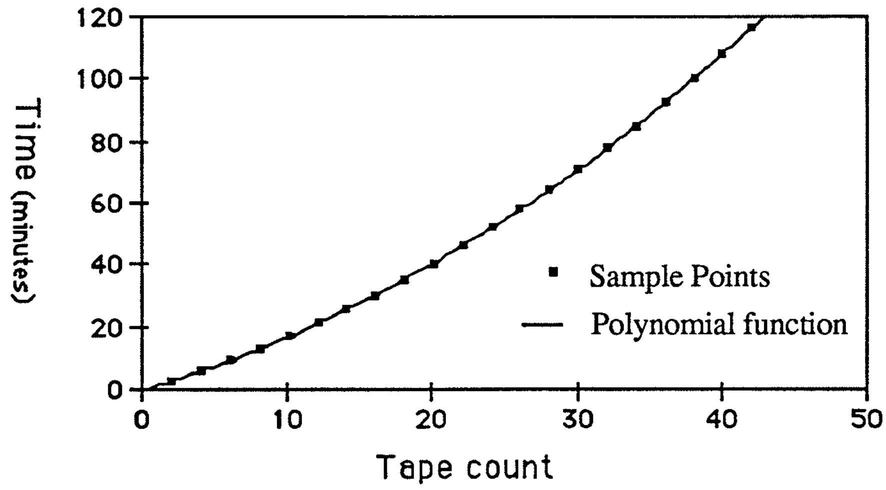
APPENDIX A

Method of aligning FLIR data and photographs to time.

Forward Looking Infrared imagery was interpreted on a JVC video cassette recorder. The tape counter recorded the speed of the full spool as the tape moved from one spool to the other. The relationship between tape count and time increased curvilinearly over the duration of a two hour tape. The common measurement medium for both FLIR and photography was time. To convert tape counts to time the amount of time elapsed in a 2:00 tape count interval was measured for all possible intervals on the two hour tape. A second order polynomial equation describes the relationship between time elapsed and tape count.



$$\hat{Y}_i = -.1354 + 1.3507\, X_{1i} + .0338\, X_{1i}^2$$

Where; $\hat{Y}_i$ = Predicted time from tape count, X_i = Tape count.

The model was used to convert the location of thermal water mass boundaries from a tape count to location in time. This time was then standardized to reflect distance from beginning of the transect. Photographs were also located in time from the beginning of each transect based on the photo frame interval.

APPENDIX B.

Identification of narwhal on 2445 aerocolor negative film.

Identification of Narwhal and Beluga Using Colour Negative Film.

(Photo. Scale 1:6000)

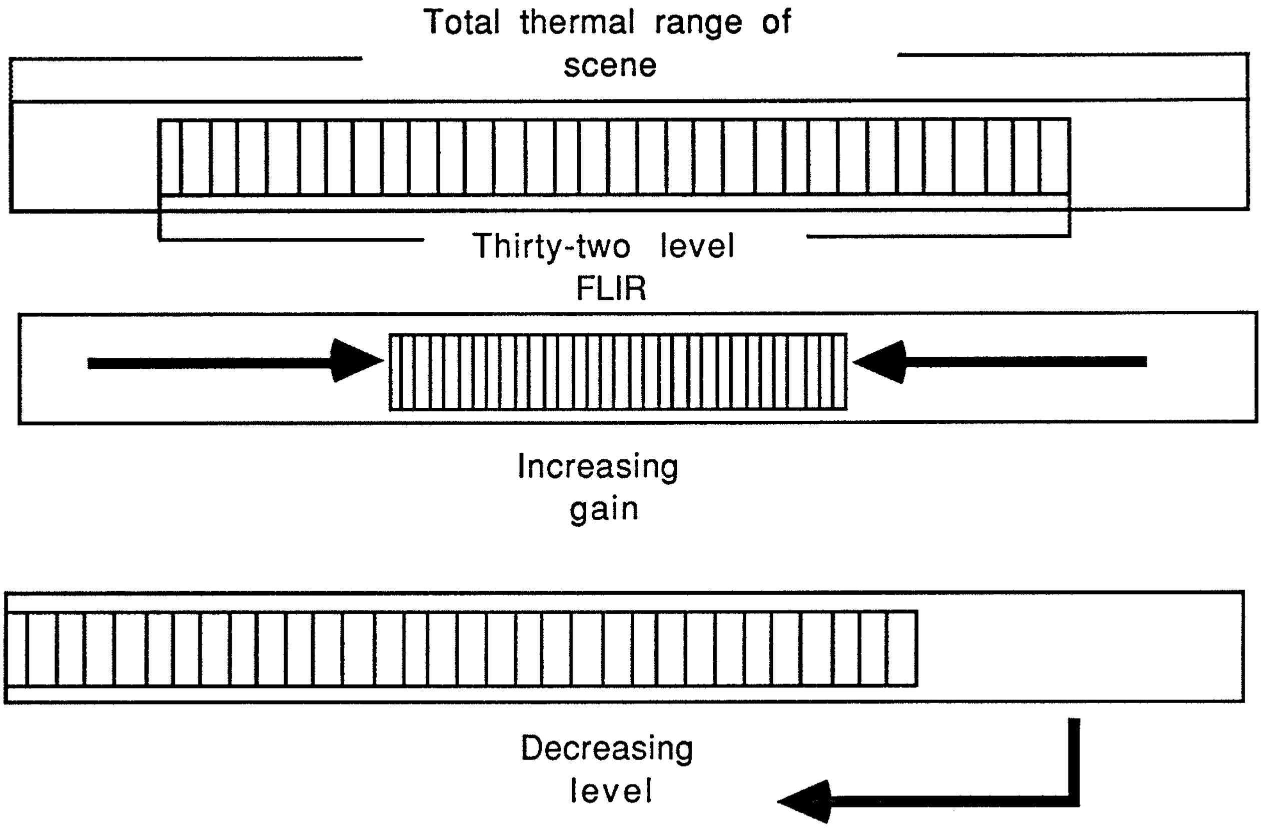
Parameter	Species	Description
Colour	Narwhal	Adults have a dark body, with a light strip down the dorsal surface. Older animals have a distinct light coloured triangle immediately posterior to the snout. When submerged animal outline quickly becomes blurred (more so than beluga). Submerged colour changes from light pink to purple with depth.
	Beluga	Adults are very dark. Colour changes from light purple to dark purple with depth. Animals are a uniform shade of colour versus the mottled colour of narwhal.
Body	Narwhal	Streamlined body (torpedo shaped). Tusks are usually visible if sea state is not too rough.
	Beluga	Beluga are wider than narwhal, more rotund. Body tapers at both ends, as opposed to the narwhal torpedo shape, which is blunt at the head.
Fluke	Narwhal	The fluke is fan shaped and the caudal peduncle is generally not visible.
	Beluga	The fluke is wing shaped and broader than a narwhal fluke. Caudal peduncle is thin but generally distinguishable.
Flippers	Narwhal	Not visible.
	Beluga	Visible only on a surfacing animal. When head and flippers are visible image resembles that of a sea bird.

APPENDIX C
Thermal Imaging with a Forward Looking Infrared (FLIR).

The Forward Looking Infrared (FLIR) is a thermal imager sensitive to radiation at a peak wavelength of 10.6 μm. This radiation is termed emitted thermal infrared. Infrared film, commonly used in 35 mm cameras, is sensitive to much shorter radiation (~0.8 to 1.0 μm). Short wavelength infrared measures reflected solar radiation whereas long wave thermal radiation is emitted from all objects on the Earths surface. The FLIR imager exploits the relationship between the amount of radiation emitted from an object and that objects temperature.

Radiation, emitted from the ocean surface passes through the atmosphere and contacts the germanium lens of the FLIR. This lens allows thermal radiation through (peak wavelength of 10.6 μm) but blocks other wavelength radiation from the sensor. The radiation that passes through the germanium lens is converted into an analogue voltage. The signal is then transformed into a video signal and recorded on a video tape recorder. Since the FLIR signal is analogue, it contains a continuous record of incident thermal radiation. This signal is transferred to grey shades by the video monitor. Visual discrimination of the number of grey levels is restricted by the human visual system, which can generally discriminate between 12 and 24 levels of grey (Gonzalez and Wintz 1987), and by the type of monitor used. The monitor used on-board with the FLIR can display 10 grey shades.

Two variable settings are available when acquiring data. The gain setting adjusts the width of temperature sensitivity of the unit. With a high gain 10 grey levels are available but over a narrower range of temperatures. Saturation occurs at the first and last grey levels (Richards 1986). This results in an increased ability to discriminate between a standard range of temperatures. The other variable setting is a level control. This scales the 10 grey levels along the total possible range of brightness of the monitor. The combination of gain and level are used to match the precision (gain) and range (level) to the thermal features being imaged



APPENDIX D.
Statistical Tests used in this Investigation.

Chi-square test for co-occurrence of narwhal and thermal boundaries.

Calculation of the chi-square statistic [5] is based on the following frequency of pairwise combinations of narwhal and thermal boundary presence or absence.. Notation for all calculations is consistent with those in the diagram.

		THERMAL BOUNDARIES		
		Present	Absent	
WHALES	Present	a 52	b 56	m=108
	Absent	c 64	d 249	n=313
		r=116	s=305	

N = m+n+r+s

Neither margin is fixed in this two by two contingency table because we have no *a priori* knowledge of the sample. The appropriate calculation for expected values for each combination of row and column (Sokal and Rohlf 1981) are:

$$\hat{E} = N\left(\frac{\text{row sum (m)}}{N}\right)\left(\frac{\text{col. sum (r)}}{N}\right)$$

$$= N\left(\frac{a+b}{N}\right)\left(\frac{a+c}{N}\right) = \frac{(a+b)\,(a+c)}{N}$$

Subtraction of observed and expected values show the relative contribution of the four possible combinations of narwhal and thermal boundary locations. Co-occurrence of narwhal and thermal boundaries provides the largest contribution to the significant Chi-square statistic in 1984. This is illustrated in a matrix of the difference between observed and expected values;

		THERMAL BOUNDARIES	
		Present	Absent
WHALES	Present	16.62 $\frac{(O-E)^2}{E}$	6.32 $\frac{(O-E)^2}{E}$
	Absent	5.74 $\frac{(O-E)^2}{E}$	2.18 $\frac{(O-E)^2}{E}$

$X^2 = 30.8659$

$$Q = \frac{ad - bc}{ad + bc} \qquad [7]$$

$$\mathrm{Var}(Q) = \frac{(1 - Q^2)^2}{4} \left\{ \frac{1}{a} + \frac{1}{b} + \frac{1}{c} + \frac{1}{d} \right\} \qquad [8]$$

The Q statistic [7] varies from 0 (no correlation) to 1 (complete positive correlation). Complete positive correlation is when either narwhal or thermal boundaries always occur with the other. A variance estimator for Q is provided in [8].

Kolmogorov-Smirnov non-parametric two sample test

Calculation of the test statistic is described in [9]:

$$D_{max} = \left| \frac{F_1}{n_1} - \frac{F_2}{n_2} \right| \qquad [9]$$

Where D_{max} is the maximum absolute difference between the ratio of the relative cumulative frequency to the total number of observations between variable 'NB' and variable 'UB'. Critical values are calculated by equation 10 when sample sizes are larger than twenty-five (Sokal and Rohlf 1981).

$$D_\alpha = K_\alpha^2 \sqrt{\frac{n_1 + n_2}{n_1 n_2}} \qquad \text{Where; } K_\alpha = \sqrt{\frac{1}{2} - \ln\left(\frac{\alpha}{2}\right)} \qquad [10]$$

The Kolmogorov-Smirnov statistic uses the absolute difference between relative cumulative frequencies to ascertain significance. The test statistic is based on the cumulative frequency distribution relative to the appropriate sample size. It is a non parametric test; the only assumption is that each variable is drawn from a continuous distribution.

Analysis of Variance

A one way analysis of variance was performed to ascertain whether a higher density of narwhal were observed closer to thermal boundaries. Homoscedasticity is an assumption of parametric analysis of variance (Neter and Wasserman 1972). For unequal sample sizes Bartlett's test is appropriate. Transformation to achieve homoscedasticity is normally conducted before resorting to a non parametric ANOVA (Neter and Wasserman 1972). A log 10(1 + X) transform was applied. The transformed variables were sufficiently homoscedastic to apply a parametric ANOVA.

APPENDIX E
List of Terms

Detection	Ability of the photo interpreter to differentiate a whale image from the background (water and/or ice).
Estimator	A statistical estimate of an unknown population parameter. The estimate is said to be *unbiased* if it approaches the true population parameter when measured over a large sample.
Heteroscedasticity	The term is used to denote unequal variances between variables. Transformations are a standard method of obtaining equal variances from a heteroscedastic dataset.
Homoscedasticity	Is used to denote equal variances between variables. This is a prerequisite for conducting parametric analysis procedures.
Identification	Ability of the photo interpreter to discriminate a detected (see Detection) image into species, maturity class or sex class.
Longitudinal Study	Analysis of observations which incorporate a temporal component. One of the principle objectives of this type of study is to observe the phenomenon of interest over time.

Parameter	Is used to denote a statistical measure of a population (ie., mean and standard deviation). The parameter is usually unknown and is estimated with an *estimator*, which is obtained by sampling the population.
Spatial Resolution	A term commonly used in remote sensing literature. It is used to describe the minimum resolveable object in the scene and the total area imaged as a fraction of the total study area (i.e., sampling fraction).
Stratification	Is a sampling technique which allows the use of *a priori* information in the design and collection of sample information. If one wished to survey business people a logical stratification variable would be commercial versus residential zoning areas.
Temporal Resolution	A term commonly used in remote sensing literature. It refers to the frequency of coverage of a particular geographic location and directly relates to our ability to detect time related changes at a particular spatial resolution level.