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Assessment of the Value of Stratified Sampling for Aerial Surveys: a Case Study of Bowhead Whales in the Beaufort Sea

E.O. Robertson and I. Robertson

Central and Arctic Region
Department of Fisheries and Oceans
Winnipeg, Manitoba R3T 2N6

January 1987

Canadian Technical Report of Fisheries and Aquatic Sciences No. 1500

Fisheries and Oceans Pêches et Océans

Canada

Canadian Technical Report of

Fisheries and Aquatic Sciences 1500

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ASSESSMENT OF THE VALUE OF STRATIFIED SAMPLING FOR AERIAL SURVEYS: A CASE STUDY OF BOWHEAD WHALES IN THE BEAUFORT SEA

by

E.O. Robertson[1] and I. Robertson[1]

Central and Arctic Region

Department of Fisheries and Oceans

Winnipeg, Manitoba R3T 2N6

This is the 5th Technical Report

from the Central and Arctic Region, Winnipeg

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[1] Ian Robertson Consulting Ltd, 18040-20 Avenue, Surrey, BC, V3S 5J9

PREFACE

This is the final report of work conducted under the terms of a Department of Supply and Services contract issued to Ian Robertson Consulting Ltd. (DSS Contract No. OSF 84-00129). Scientific authority for the contract was M.C.S. Kingsley, Freshwater Institute, 501 University Crescent, Winnipeg, Manitoba, R3T 2N6.

This study was funded by the Northern Oil and Gas Action Program (NOGAP), through the Department of Fisheries and Oceans, Western Region (now the Central and Arctic Region). It is one of a series of studies being executed under NOGAP Project B.1, to assess the implications of vessel traffic on Arctic marine mammals.

This document constitutes NOGAP Report B.1.5.

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Cat. no. Fs 97-6/1500E ISSN 0706-6457

Correct citation for this publication is:

Robertson, E.O., and I. Robertson. 1987. Assessment of the value of stratified sampling for aerial surveys: a case study of bowhead whales in the Beaufort Sea. Can. Tech. Rep. Fish. Aquat. Sci. 1500: iv + 28 p.

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ABSTRACT

Robertson, E.O., and I. Robertson. 1987. Assessment of the value of stratified sampling for aerial surveys: a case study of bowhead whales in the Beaufort Sea. Can. Tech. Rep. Fish. Aquat. Sci. 1500: iv + 28 p.

The results of the 1981-1984 monitoring surveys of bowhead whales (Balaena mysticetus) in the Beaufort Sea were re-analyzed to assess the feasibility of future stratified sampling. Within a study area bounded by 72°N, the Beaufort Sea coast, 128°W and 141°W, the original whale observation data were used to assign sightings to 130 subareas of equal area. Cluster analysis was chosen as the method of investigating the location, dimensions, and stability of the density pattern of whale sightings. Variance in annual abundance prompted the transformation of the subarea density data to ranks, and the cluster analysis was undertaken using a contiguity constraint. This meant only adjacent areas could be grouped.

Cluster analysis identified a high-density stratum consisting of 45 subareas in which 89% of the whales were sighted, and a low-density stratum of 67 subareas in which only 11% of the whales were sighted. The remaining 18 subareas were over land. The high-density stratum was distributed approximately in an east north-east direction from Herschel Island to an area north of Cape Dalhousie, but its boundaries with the low-density stratum were not stable from year to year.

Population estimates correspond closely with those reported in the annual monitoring reports. These estimates confirm that in 1983 and 1984 lower numbers of bowhead whales used the area established in this study. The population estimates presented here are qualified by an estimate of variance, which is recommended as a minimum requirement for population monitoring studies. The study also recommended that bowhead whale surveys should continue to be flown in evenly-spaced sequential strip transects, but that the data be regrouped by location into approximately square subareas for density analysis.

Key words: Balaena mysticetus; surveys; transect; population number; approximation.

RÉSUMÉ

Robertson, E.O., and I. Robertson. 1987. Assessment of the value of stratified sampling for aerial surveys: a case study of bowhead whales in the Beaufort Sea. Can. Tech. Rep. Fish. Aquat. Sci. 1500: iv + 28 p.

Les résultats des relevés de contrôle des baleines boréales (Balaena mysticetus) dans la mer de Beaufort qui ont été effectués de 1981 à 1984 ont été analysés à nouveau afin d'évaluer s'il serait possible, à l'avenir, de procéder par échantillonnage stratifié. À partir des données initiales d'observation des baleines, chaque cas d'observation a été situé dans une des 130 sous-zones d'égale superficie qui constituent la zone d'observation, limitée par le 72°N, la côte de la mer de Beaufort, le 128°O et le 141°O. On a choisi l'analyse de grappes pour établir le lieu, les dimensions et la stabilité du modèle de densité des cas d'observation des baleines. En raison des variations de l'abondance d'une année à l'autre, on a dû prendre les données de densité des sous-zones et les exprimer en rangs et on a procédé à l'analyse de grappes, soumise à une contrainte de contiguité. Ainsi, seules les sous-zones adjacentes ont pu être groupées.

L'analyse de grappes a permis de mettre en lumière une strate de grande densité renfermant 45 sous-zones où 89% des baleines avaient été observées et une strate de faible densité renfermant 67 sous-zones où 11% seulement des baleines avaient été observées. Les 18 autres sous-zones se trouvaient sur la terre ferme. La strate de grande densité se situait de façon générale dans le sens est-nord-est à partir de l'île Herschel jusqu'à un point au nord du cap Dalhousie, mais ses limites avec la strate de faible densité variaient d'une année à l'autre.

Les estimations de population correspondent d'assez près à celles qui sont données dans les rapports annuels de contrôle; elles confirment qu'en 1983 et 1984, il y eu moins de baleines boréales dans la zone visée par l'étude. L'estimation de la population que l'on donne dans ce rapport fait l'objet d'une réserve, celle de l'estimation de la variance, qui est recommandée comme exigence minimale pour les études de contrôle de population. Il est également recommandé que le contrôle des baleines boréales se fasse encore suivant des transects en bande à la suite, également espacés les uns des autres, mais que les données soient regroupées par endroit, dans des sous-zones à peu près carrées, aux fins d'analyse de la densité.

Mots-clés: Balaena mysticetus; évaluations; transect; nombre de la population; approximation.

INTRODUCTION

The first step in monitoring the abundance and distribution of a rare and widely dispersed animal over a large study area is usually a uniform survey covering the entire area. The results of the preliminary investigation allow the scientist to evaluate the efficiency of the sampling method, the optimum size of sample unit, the level of effort required to obtain the desired precision of estimate (or, often, the precision that can be expected within the predetermined budget), and to check for the presence of a large-scale spatial pattern that would make stratification desirable. Frequently, this "refit" of the survey methods is not done. Preliminary sampling methods are commonly repeated for years, often because this consistency is seen as the only means of making data comparable, or because the logistics of a difficult field situation are hard to change. In the case of transect sampling, the assumptions in the data analysis methods (e.g. of randomized transects within areas of homogeneous distribution) are commonly ignored.

Hidden bias and imprecision are only two of the potential costs of project design failures in survey methods and data analysis. In the case of population abundance and distribution studies, the annual estimates may be consistently high or low, the confidence limits incorrect, and the detection of significant changes in abundance or spatial distribution impossible.

Our object in this study has been to examine the results of oil industry sponsored aerial surveys of bowhead whales (Balaena mysticetus) in the Beaufort Sea from 1981 to 1984. The overall purpose of this exercise has been to examine the feasibility of stratified sampling: in a sense, conducting that "refit" of survey methods.

The evolution of this survey program from the first bowhead sightings in inshore waters in 1976 to its consistent format in 1981 covering a large portion of the southern Beaufort Sea reflected an expanding exploration zone offshore and conflicting survey objectives. The latter included limits imposed by survey logistics (e.g. aircraft specifications, weather, project funding) and the need for information on whale distribution and movements particularly as they related to the location and intensity of exploration activity. A systematic survey design supported these objectives, with repeated surveys providing better information on movements. There was also a demand for accurate abundance estimates owing in part to the rare and endangered status of the bowhead whale. Estimates of abundance are enhanced by randomization of survey design. In this case, practicality dictated the systematic approach. In our analysis data from eight surveys (two in each year) have been examined in order to determine if a stratification of the study area would enhance population estimates and if a corresponding new distribution of sampling effort would be appropriate for future surveys. Stratification in our approach is based on areas of "homogeneous" whale densities as determined by the 1981-1984 surveys rather than on homogeneous physical conditions.

SURVEY AREA AND METHODS

STUDY AREA

In 1981, two sets of modified strip transects were flown on approximately evenly spaced north-south transects between the south shore and 70° 30' to 72° latitude, and from East Amundsen Gulf to the Alaskan border (Davis et al. 1982). The study area was divided into five blocks based on operational considerations, and these blocks were subsequently used as "strata" for population estimations. A ratio estimation procedure was used to combine results from transects of different lengths (referenced to Caughley and Grigg 1981) in order to estimate mean density (per km^2), variance and total number of animals within each stratum. The resulting population estimates were corrected for unseen (surface) and submerged animals in order to arrive at a final population estimate.

In subsequent years (1982-1984), the surveys have focused on the area south of latitude 72 and between 128 and 141 degrees longitude (Fig. 1). Our analysis has been restricted to sightings within these boundaries, though there has been minor year to year variation in study area dimensions extending beyond these limits in some cases. The latter are not considered here. The survey method of evenly spaced north-south transects, flown in sequential order (west to east), has been repeated. Although the locations of whale sightings were recorded, the basic sampling unit of all surveys has been the transect. These transects are approximately 1.6 km wide and up to 330 km long. Each transect combines observations in the near-shore, shelf-break and deep-water area.

The 1982 surveys were not analysed to produce a population estimate, although the raw data allow comparison with other years (Harwood and Ford, 1983). No attempt was made to identify strata proportional to whale density, industrial activity (i.e. impact and control subareas), or oceanographic phenomena.

Similar methods were used again in the 1983 census (McLaren and Davis 1984). An apparent clustering of sightings in close proximity to the "shelf break" (i.e. steep drop of 300± m within a few km) was observed, and an attempt was made to test the significance of this congregation. Unfortunately, an inappropriate statistical test was employed (i.e. a contingency table based on counts within depth strata, rather that a test for different density close to the shelf break), and the tests failed to confirm the apparent spatial pattern. It should be noted that if the shelf break is in fact a locus of concentration for bowheads, then stratification by depths would not improve the data analysis, since the area of concentration would be on the border between strata (assuming that the normally charted isobaths of 50, 100, and 200 m were used).

The 1984 census has not yet been reported, but the raw data have been made available to us (Harwood, pers. comm.). There has been a growing interest in a number of oceanographic phenomena that might be associated with bowhead distribution.

Visual examination of the four years' bowhead sightings does not at first glance indicate a spatial pattern of whale density in the Beaufort Sea (Fig. 2 - 5). Eliminating those areas where whales are seldom seen, the majority of sightings appear to be circumscribed in an eliptical zone that lies approximately west by southwest to east by northeast, roughly the location of the shelf break. Thus most of the north-south transect lines pass through this high density zone as well as unequal areas of low density. The blocks established in 1981 include unequal portions of the high-density and low-density zones. Therefore, the population estimates based on transect densities or block densities may be biased.

The basic data set for this investigation consisted of latitude and longitude for each whale sighting, transect (code or number), number of whales in the group, and whether they were "on-transect" (as operationally defined in the corresponding year's report) or "off-transect". There were eight surveys in the study area (longitude 128 to 141) but the boundaries of coverage varied from year to year, as did the level of effort.

METHODS

Working division of the study area

Cluster analysis was chosen as the method of investigating the location, dimensions and stability of the density pattern. The availability of eight surveys made this method appropriate; in addition, it is free of assumptions about physical influences on animal distribution. In the case of bowhead whales, the units used for clustering needed to be small enough to give good resolution to the spatial pattern, yet large enough to have several transect segments (i.e. subsamples) in most surveys. For practical reasons, the application of stratification to aerial surveying requires use of latitude and longitude (or loran) definitions rather than ocean depths (not visible from the air) or irregular contours on charts. It was decided to use degrees of longitude to divide the study area into 13 north-south zones and 10 east-west divisions such that the surface area within each of the resulting 130 subareas would be equal. Figure 6 shows the basic scheme. The final working number of subareas is 110, since 18 of the 130 are over land, and two were never surveyed. Each subarea covers approximately 350 square nautical miles, except for those that overlap the south shore. (Nautical miles, while they may seem quaint in this metric age, lend themselves very well to analysis based on Azimuthal projection maps. For conversion, 1 n.mi. = 1.852 km, and 1 n.mi.^{2} = 3.430 km^2.)

While these 110 subareas represent equal surface area, the frequency with which they were surveyed varied considerably over the four years. Figure 6 shows the frequency of coverage over the eight surveys. The actual coverage of each of the eight surveys is shown in the Appendices.

It should be noted that our analysis covers only the "core" survey area (128 through 141 degrees longitude) and only mid-August through September data. Data from intensive or irregular transects within this study area have been included. The results of more easterly transects as flown in 1984, are not included in this analysis.

Unequal sampling between subareas means variable confidence limits on estimated whale densities in each subarea. No alternative subdivision of the study area can entirely overcome inequalities in the original survey coverage, and larger subareas would not entirely overcome the reduced coverage in the north and northwest parts of the study area.

Deriving and ranking relative densities

The original whale observation data (i.e. latitude, longitude, group size, on- or off-transect) were used to assign sightings to subareas. Since the number of on-transect sightings was very low for 1983 and 1984, it was decided to use both on- and off-transect sightings. This provides better indication of relative abundance per subarea, although it is recognized that the off-transect observations are subject to more inconsistency between surveys. In particular, there is no clearly specified off-transect survey width. Davis et al. (1982) discussed lateral detection distances, including sightings at greater that 6000 m, but it is difficult to guess how one might appropriately compensate for the attrition of accuracy with distance. We have assumed that the probability of observing animals off-transect was equal in the four years. For the purpose of calculating an approximate density for each subarea from these data, the transect width was adjusted to three times the reported on-transect width. These densities are, therefore, relative and have no absolute interpretation. Figure 7 shows the averages of these densities (i.e. the mean of all surveyed years) per subarea.

The average relative densities shown in Figure 7 are strongly influenced by the 1981 sightings of 272 whales (between 128°W and 141°W), while the other three years (combined) totalled only 331 whales. Since the purpose of defining survey strata is to reduce within-stratum variation independent of total abundance (i.e. stable over different years), the stratification process must be based on a description of relative density that equalizes the years with different levels of abundance.

Transformation of the density data to ranks was chosen as the best solution. Ranks ranging from 1 to a maximum of 103 (representing a maximum of 103 subareas covered in one survey) were assigned to all surveyed subareas within each of the eight surveys, with ties being assigned average ranks. Since there were many subareas with zero density, the average rank

assigned to zero density subareas ranged from 18 (August, 1982) to 38 (both 1984 surveys). Average ranks for all surveyed years are shown in Fig. 8.

Cluster analysis

A useful stratification must be based on the stable (i.e. repeatable) patterns of relative density over the four years as well as accommodating high occasional observations. While it is possible to stratify a study area intuitively with the guidance of density maps, it is very difficult to determine the stability of the strata boundaries. Cluster analysis, using the ranks in the eight surveys as eight sorting keys, can be used to identify optimal density strata and to test their stability over the four different years.

The program OGROUP was used to perform the cluster analysis (Patterson and Whitaker 1982). OGROUP is a hierarchical grouping analysis which at each grouping step selects the pair of items (subareas) or groups with the minimum error, defined in this application as:

Error value = (sum of squared differences between corresponding ranks in 8 surveys)/(no. of subareas in the potential group).

In this application of OGROUP, a contiguity constraint was employed: i.e. only adjacent subareas could be grouped. This produces strata that are not split into discontinuous areas. However, the process may be limited from identifying the most similar sets of subareas where they are spatially separated. (Note that the same analysis run without the contiguity constraint may be an optimal method of identifying good control areas for studying specific impact issues.)

The results of the cluster analysis can be examined at any number of groups (i.e. strata); in this study the levels of 10, 5, 3 and 2 strata were examined.

There is no direct statistical test for the stability or reliability of a stratification scheme. One indirect method of examining the stability is to use a modified "jacknife" procedure: this newly derives a stratification using three years of data rather than four. There are four possible subsets of three years, and the resulting stratification patterns can be compared with each other and with the "optimal" fit based on four years' data.

The jacknife stratifications can also be compared with the data from the reserved years; e.g. how well would a stratification based on three years have worked on the fourth year?

The significance of migratory movements on bowhead distribution was examined by clustering August surveys separately from September surveys.

Finally, the frequency distribution of whale group sizes was examined to determine if nonrandom dispersion is a significant element in estimating whale population size. Significant deviations from random dispersion, or differences in group sizes in different strata, would affect the sampling effort required.

RESULTS

DISTRIBUTION

The results of the cluster analysis at the levels of 10, 5 and 3 strata were not sufficiently stable to warrant further investigation. Instead, two strata are identified: a "high-density" stratum consisting of 45 subareas in which 89% of the whales have been observed, and a "low-density" stratum of 67 subareas in which only 11% of the whales have been found (Fig. 9).

The first test of this stratification was to calculate the proportion of the estimated population that was observed in the two strata in each of the four years (Table 1). To arrive at these figures, on-transect data from each transect in each year was divided into the segment within the "high-density" stratum and the one or two segments in the "low-density" stratum. These transect segments were then analysed via the ratio estimation procedure (Caughley and Grigg 1981) to arrive at density estimates and variances (Table 1).

It should be noted that the high-density stratum was surveyed very consistently during the four years: in all but one survey, 41 or more of the 45 subareas in this stratum were surveyed. The low-density stratum was not consistently covered. In 1982, only 12 (August) and 15 (September) of the possible 67 subareas in this stratum were flown. In 1983, only half of the low-density stratum was surveyed. Thus, the under sampling of the low-density stratum in 1982 and 1983 may tend to deceptively enhance the apparent consistency and "fit" of the stratification. The difference in whale densities between high and low strata is much less in 1981 and 1984, when more of the low-density stratum was flown.

Figures 10 - 13 show high- and low-density strata as derived by the jacknife procedure, using cluster analysis on three years' data in each case. It is obvious that the strata boundaries vary considerably from case to case, and thus the precision with which high- and low-density areas can be defined is low. Comparison with whale densities observed in the reserved year in each case (Table 2) according to the strata derived from the other three years shows that the low-density stratum did have lower densities in all cases but one (August, 1981). The lack of complete coverage of the entire study area in all years prevents an exact comparison.

The main conclusion to be drawn from examining the jacknife results is that the dimensions and boundaries of high- and low-density areas are not stable features of bowhead distribution in this environment. Therefore, it would be unwise to plan a major redistribution of sampling effort based on past years' distribu-

tions. Also, the use of different sampling methods such as sequential sampling would be inappropriate.

MIGRATORY MOVEMENTS

During the annual survey period, westerly movements by bowhead whales are predicted. This conforms to the perceived pattern of the whales moving from their mid-summer concentrations in Amundsen Gulf to winter concentrations in the Bering Sea (Fraker et al. 1978). This westerly movement explains the traditional practice of flying the transects sequentially west to east (Harwood and Ford 1983; McLaren and Davis 1984). The observations to date have not shown higher densities in the western area in September surveys, and thus do not fit the predicted pattern.

We compared the August and September observations using cluster analysis on the ranked density data. At the level of two groups, the results indicate a more dispersed and easterly distribution of whales in September compared to August (Fig. 14 and 15). (Note that the high- and low-density strata in these two figures are not directly comparable, i.e. the density in the high-density stratum in the August cluster is higher than that of the September cluster.) Such a pattern in a closed population would suggest easterly movement, but in this case immigration of whales into the eastern portion, as well as dispersion of the August concentration near the MacKenzie Delta, account for the pattern. The only implication of this finding for survey data analysis is a caution against extrapolating survey results from a portion of the study area to unsurveyed (or less intensively surveyed) portions of the study area, especially in earlier or later surveys.

Without tagged or otherwise identified animals to observe, the rate of migration and its implications to overall population estimates cannot be addressed. Efforts during the last few years to establish a photographic record of individual whales will help overcome current limitations.

WHALE GROUP SIZE

Within the study area used in this report, there were 453 whale sightings (on + off transect) during the four years. Of these, 363 were singleton whales; only 10 groups numbering more than three whales were observed (Fig. 16). The mean group size was 1.3 whales. On the basis of these data, clumped distribution does not appear to be an important factor in estimating whale density.

There are two factors that cannot be addressed by an examination of the available group-size data:

1. Low visibility of whales due to suboptimal sea state and submergence. The correcting factors derived by Davis et al. (1982) indicate that less than one-fifth of the whales present in a transect are observed. The survey method makes it impossible to distinguish between five unassociated singleton whales, of which one is seen, and a group of five whales of which one is seen. In other words, the preponderance of singleton observations in the existing data does not rule out the possibility that whales may commonly associate in groups as large as five.

2. The notion of group includes a concept of space: how far apart might several associated bowhead whales be? The operative distance for the 1981 data was "less than 10 body lengths" (W.J. Richardson, LGL, unpublished data).

While clumped distribution does not appear to be an important concern for the purposes of population estimation, the testing of hypotheses concerning attracting to or avoidance of oceanographic or man-made phenomena will require more sophisticated understanding of whale group behaviour. Our conclusion is that the organization of the present data probably tends to underestimate group size and association/communication between whales.

DATA REGROUPING

As a byproduct of the reexamination of data in this study, we have had the opportunity to think about the logistics and efficacy of surveying whales via aerial transects. The practical advantages of flying parallel sequential strip transects are overwhelming in this field environment, compared to any statistically superior method (e.g. properly randomized transects). The problem arises with using each transect as an independent sampling unit. By using transects as sampling units information about specific locations of whales is lost, and sightings from different proportions of different habitats are needlessly combined.

The reworking of the location data that was done to divide each year's observations into the 110 subareas used for cluster analysis is an example of a legitimate alternative for analysis of aerial survey data. As long as the locations of effort and sightings are known, the study area can subsequently be divided into subareas of any size that suits the investigation at hand. Square subareas are far more likely than strip transects to be acceptable homogeneous with respect to environmental factors and whale density. Use of such subareas helps to prevent problems in dealing with small, localized areas of intensive effort (i.e. findings are easily applied only to the subareas involved), and also with unusual occurrences such as the group of 22 whales observed on-transect in 1983. Perhaps the greatest advantage is that such data management would make it far "safer" for the investigators to spend more survey time covering areas where whales are numerous, without biasing the density estimates of other areas.

Using transect segments within subareas as sampling subunits (to estimate within-subarea

variance), and the calculation methods described for the jacknife density estimates, population estimates for the four years have been prepared (Table 3). The smaller standard errors of these estimates reflect the greater homogeneity of the subareas as compared to the strata employed in the 1981 monitoring study (Davis et al. 1982). Since the strip transects pass through unequal areas of high- and low-density, their heterogeneity is greater. Our population estimates correspond closely with those reported in the annual monitoring studies. These confirm that in 1983 and 1984 lower numbers of bowhead whales used the area established in this study. One advantage of our approach is that population estimates are qualified by an estimate of variance. We recommend this as a minimum requirement for population monitoring studies.

We also recommend that bowhead surveys continue to be flown in evenly spaced sequential strip transects, but that the data be regrouped by location into approximately square subareas for density analysis.

ACKNOWLEDGMENTS

Michael Kingsley, Freshwater Institute Winnipeg acted as scientific authority, and along with Mark Fraker, provided constructive comments on the project design. Eric Marshall, Brigitte deMarch, Gordon Koshinsky, Pamela Norton, Michael Kingsley and an anonymous reviewer provided comments on the manuscript.

Lois Harwood and Wayne Duval, of ESL Limited, John Richardson and Chris Holdsworth of LGL, and Herman Dirschl of COGLA, made available the original survey data from the 1981 to 1984 bowhead whale survey programs.

Brad Humphreys and Vince Poulin prepared the figures and advised on graphic presentation, respectively.

The project was supported by the Northern Oil and Gas Action Program (NOGAP).

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Table 1. Densities of bowhead whales (in $n.mi^{-2}$) in high- and low-density strata.

	Covered subareas	Density ± SD	Percent of estimated population
High-Density Stratum			
1981 August	41	0.132 ± 0.033	65.3
September	44	0.101 ± 0.034	88.8
1982 August	45	0.207 ± 0.013	100.0
September	45	0.126 ± 0.012	100.0
1983 August	45	0.011 ± 0.005	87.6
September	44	0.068 ± 0.019	100.0
1984 August	38	0.056 ± 0.010	81.0
September	41	0.128 ± 0.043	91.2
Low-Density Stratum			
1981 August	57	0.046 ± 0.012	34.7
September	45	0.012 ± 0.006	11.2
1982 August	12	0.0	0.0
September	15	0.0	0.0
1983 August	26	0.003 ± 0.002	12.4
September	33	0.0	0.0
1984 August	48	0.001 ± 0.001	19.0
September	46	0.011 ± 0.007	8.8

Table 2. Densities of bowhead whales (in $n.mi^{-2}$) in study area strata, based on jacknife procedure. See text.

		Number of Sub-areas in stratum		Density observed in "reserved" year	
		High	Low	High	Low
1981	August	39	15	0.091	0.102
	September			0.092	0.028
1982	August	55	1	0.155	0.00
	September			0.096	0.036
1983	August	34	31	0.061	0.022
	September			0.118	0.044
1984	August	28	58	0.064	0.012
	September			0.100	0.046

Table 3. Comparative population estimates of bowhead whales in the Beaufort Sea, 1981-1984.

Survey	Effort # subareas	Whales seen on-transect	Published estimates	Revised estimates
Aug 19-29, 1981	103	108	2918 ± 1015	2567 ± 702 SE[1]
Sept 7-14, 1981	79	44	1835 ± 637	1539 ± 421
Aug 18-24, 1982	57	51	2831[2]	2863 ± 782
Sept 5-13, 1982	60	37	2029	1737 ± 475
Aug 19-24, 1983	71	39	1057	925 ± 253
Sept 6-11, 1983	77	30	1751	1921 ± 525
Aug 18-27, 1984	87	18	N/A	833 ± 228
Sept 6-18, 1984	88	34	N/A	1829 ± 500

The standard errors are the square roots of variances calculated as follows:

[1] The uncorrected variance is calculated as the sum of the subarea variances (method developed for transect data by Caughley and Grigg (1981) as cited in Davis et al. (1982) p. 41 and 42) and is corrected for unseen and submerged whales using the formula (Davis et al. (1982) pg. 58):

$$\mathrm{var}(T_c) \approx \frac{T^2}{P_1 P_2} \left[\frac{\mathrm{var}\ (T)}{T^2} + \frac{\mathrm{var}\ (P_1 P_2)}{(P_1 P_2)^2} \right]$$

where T = population estimate (uncorrected)

P_1 = 0.685; correction factor for unseen surface whales

P_2 = 0.261; correction factor for submerged whales

var (T) = sum of the subarea variances

var $(P_1 P_2)$ = 0.002388 estimates in Davis et al. (1982)

[2] Estimate of Harwood and Ford (1983) corrected for animals present at the surface but not seen, i.e. divided by 0.685 (Davis et al. 1982).

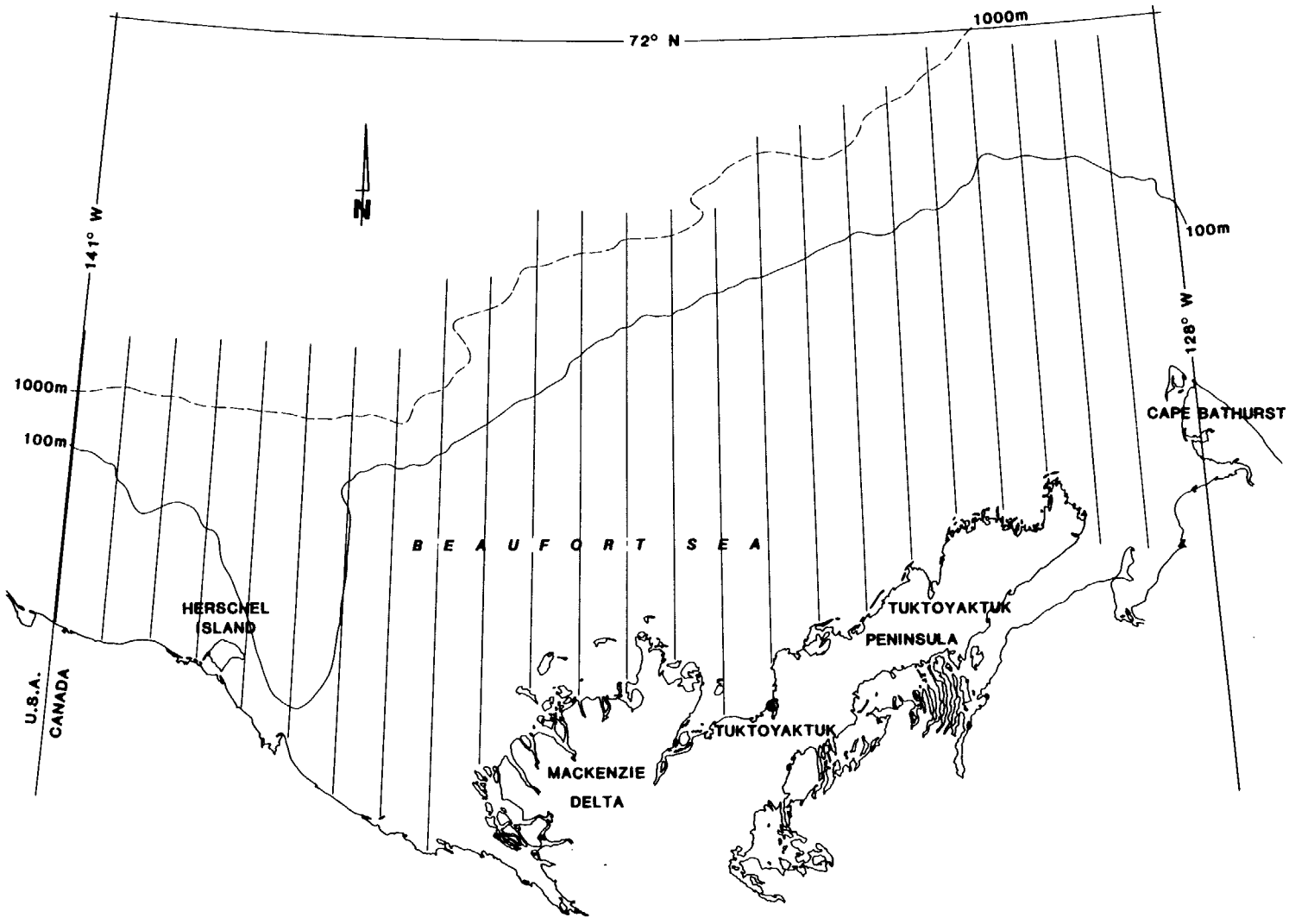


FIGURE 1: BEAUFORT SEA, SHOWING TYPICAL (1983) TRANSECT LINES FLOWN IN 1981-1984 BOWHEAD WHALE SURVEYS.

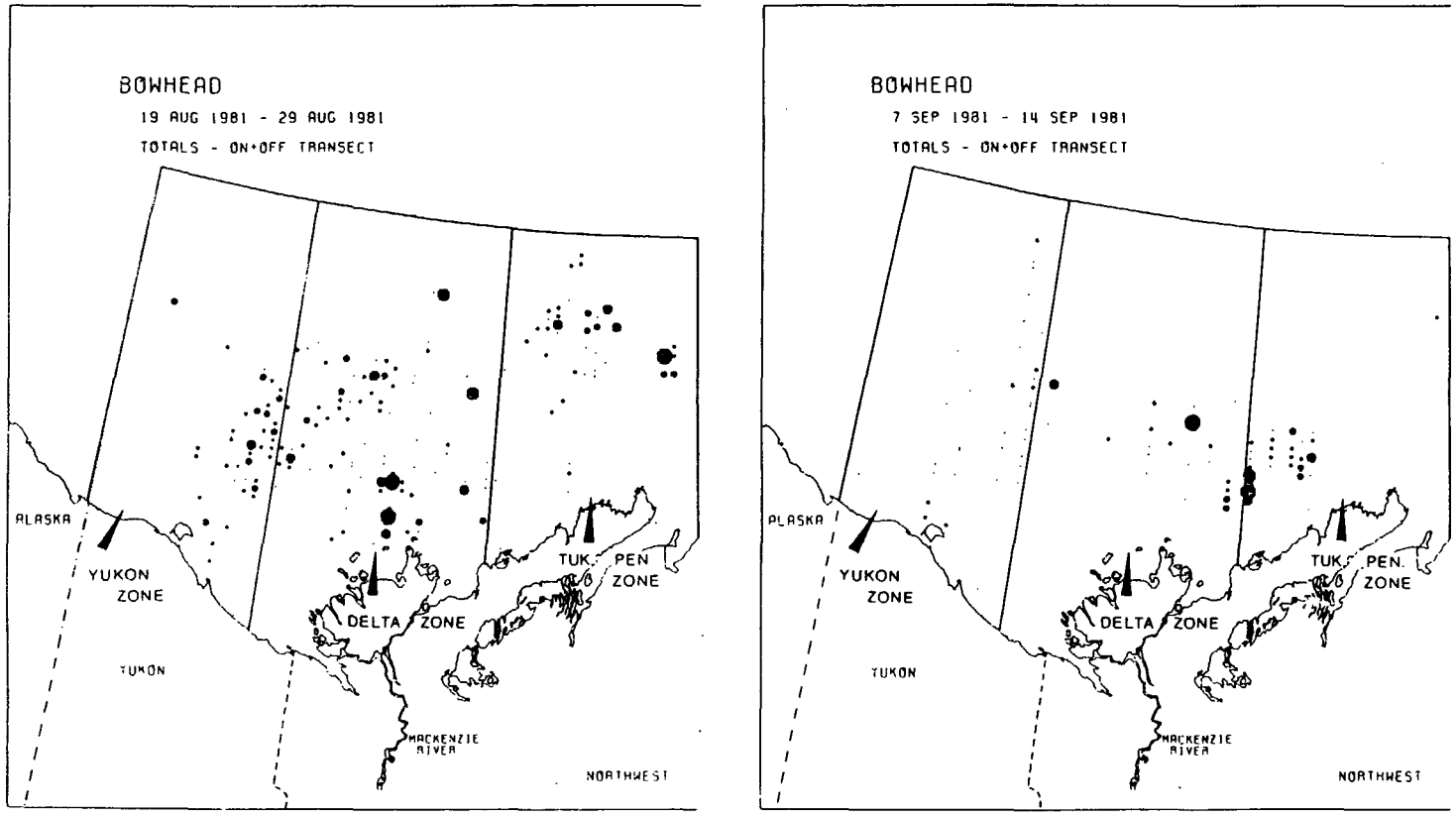
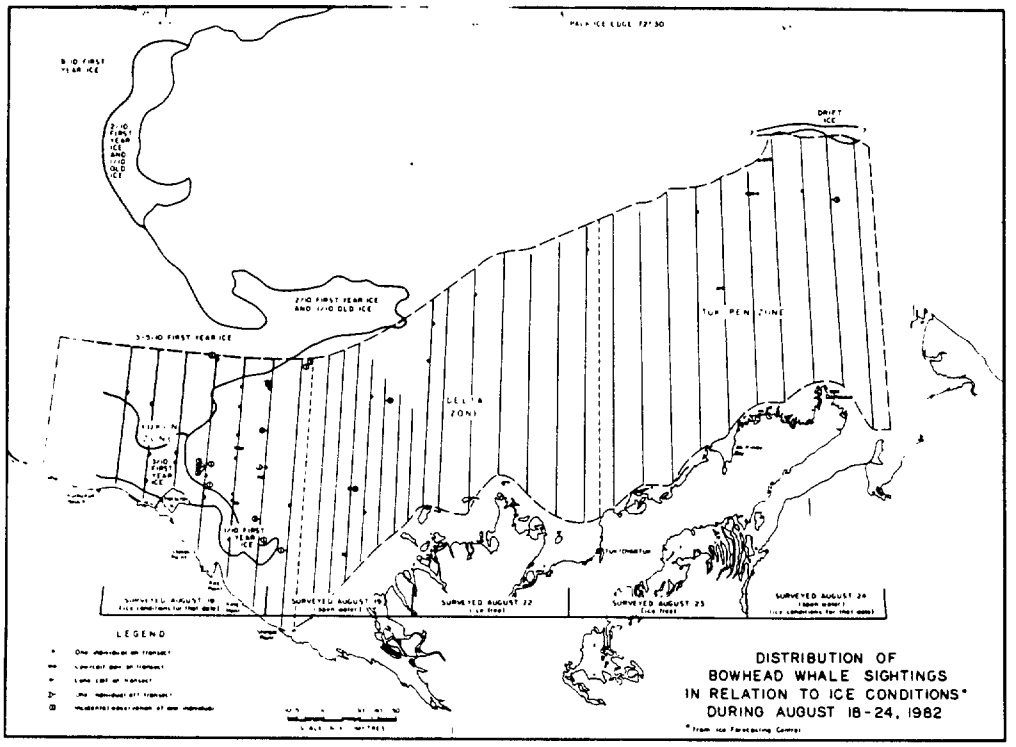


FIGURE 2: BOWHEAD WHALE SIGHTINGS - SYSTEMATIC SURVEYS, AUGUST 19-29 AND SEPTEMBER 7-14, 1981.
(From Davis et. al., 1982.)



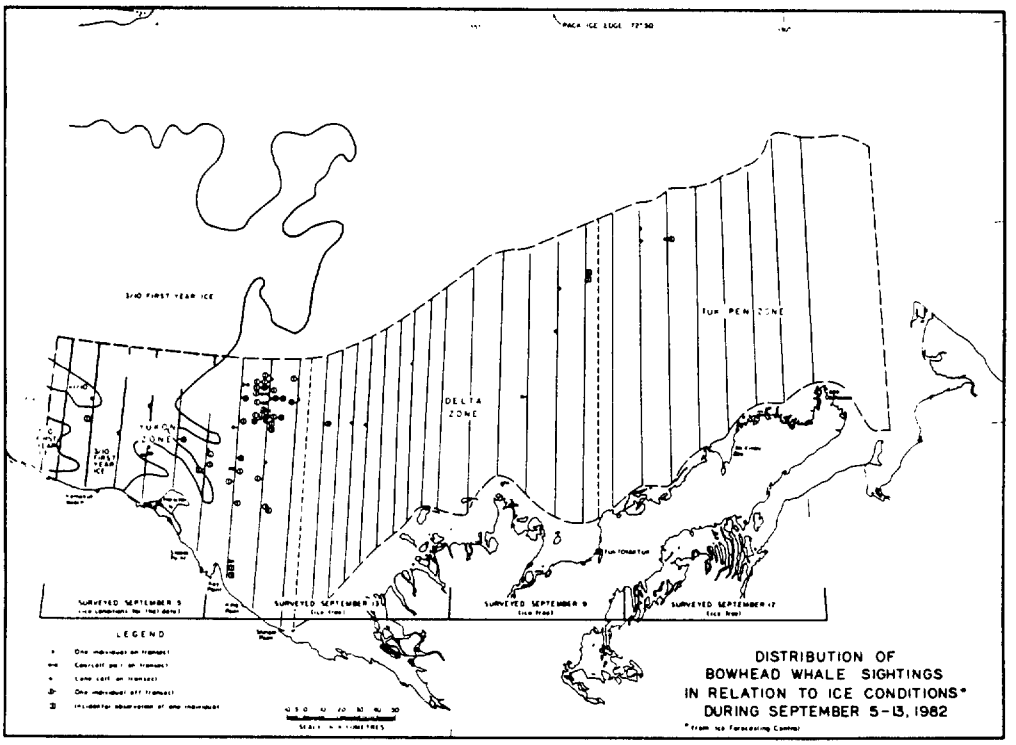


FIGURE 3: BOWHEAD WHALE SIGHTINGS - SYSTEMATIC SURVEYS, AUGUST 18-24 AND SEPTEMBER 5-13, 1982.
(From Harwood and Ford, 1983.)

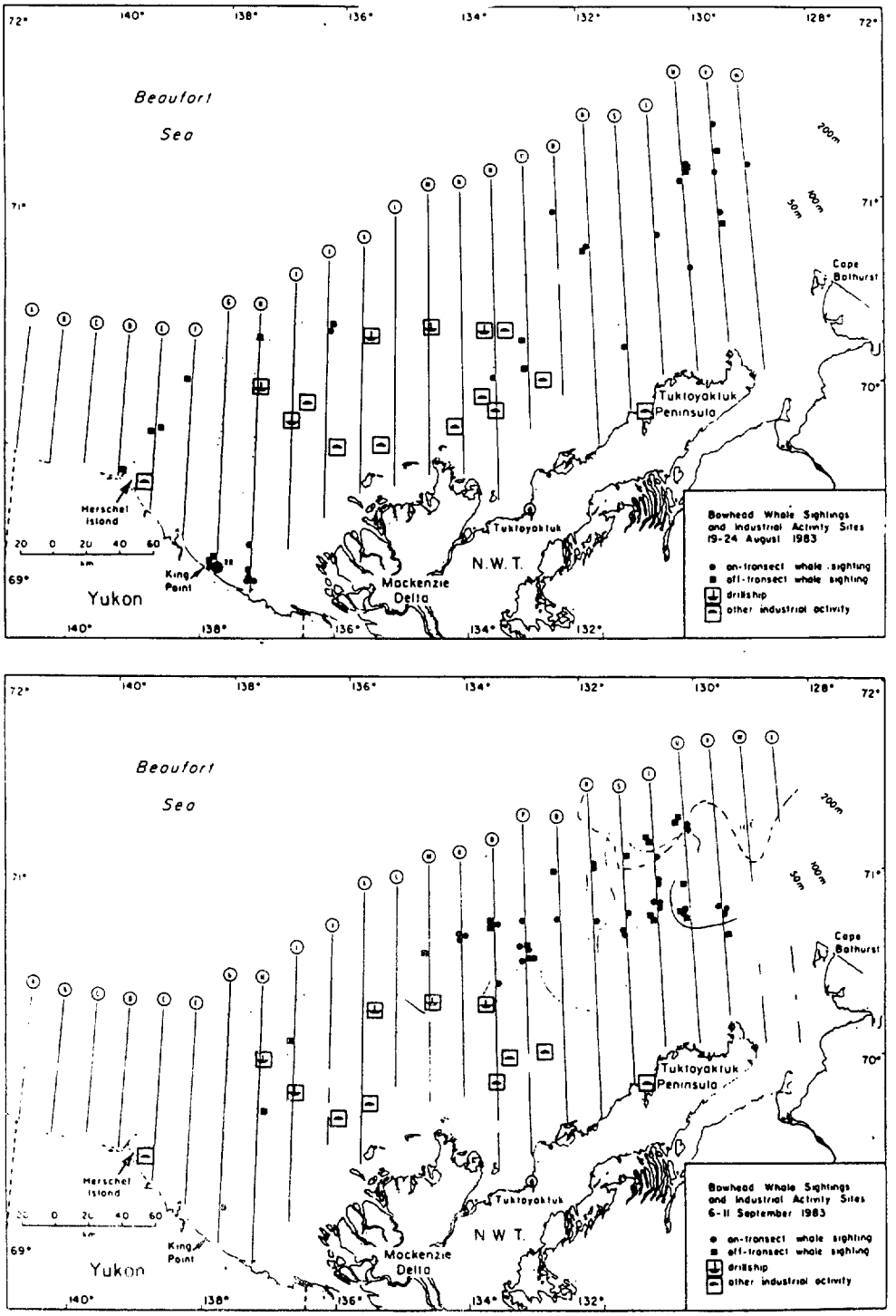
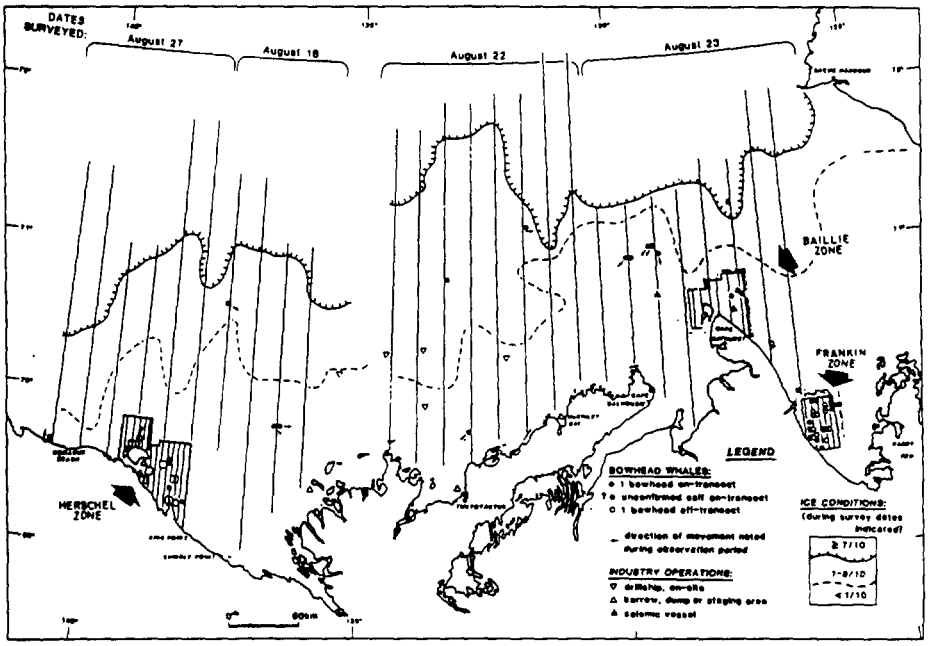


FIGURE 4: BOWHEAD WHALE SIGHTINGS - SYSTEMATIC SURVEYS, AUGUST 19-24 AND SEPTEMBER 6-11, 1983.
(From McLaren and Davis, 1984.)



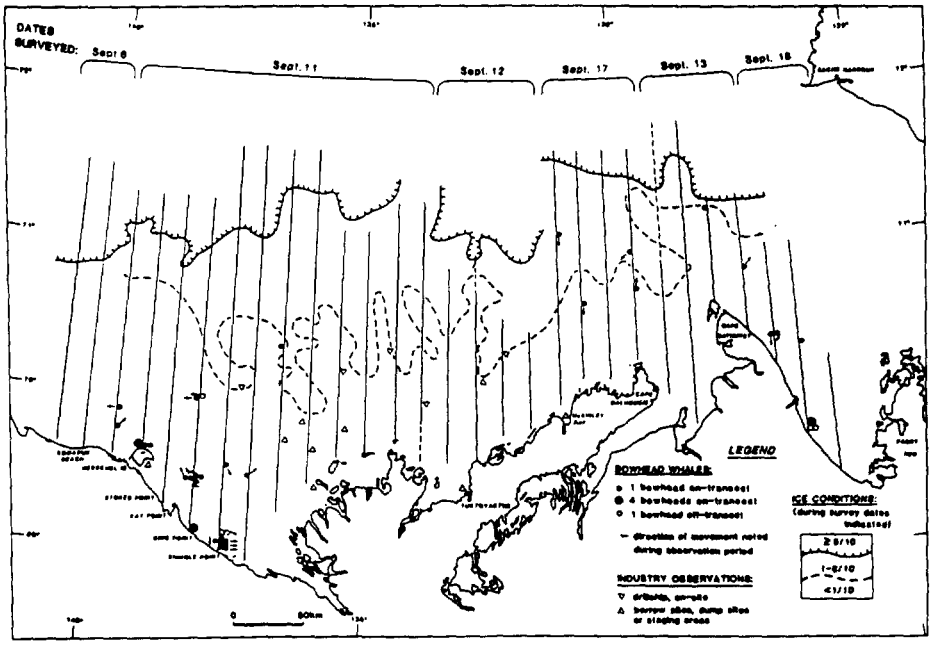


FIGURE 5: BOWHEAD WHALE SIGHTINGS - SYSTEMATIC SURVEYS, AUGUST 18-27 AND SEPTEMBER 6-18, 1984.

(From Harwood and Borstad, 1985)

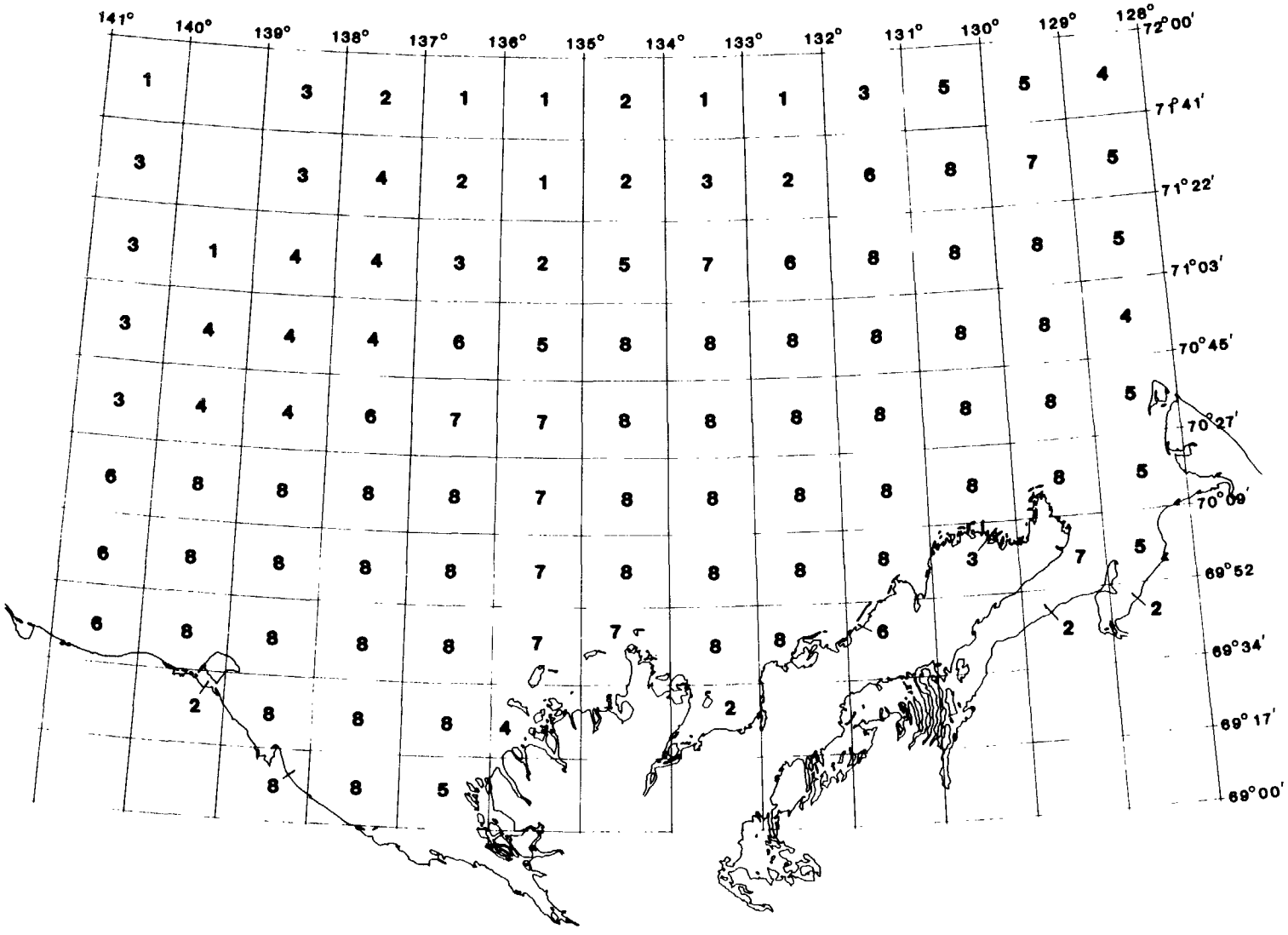


FIGURE 6: STUDY AREA GRID, SHOWING NUMBER OF OBSERVATIONS WITHIN EACH SUBAREA BOWHEAD WHALE SURVEYS 1981-1984

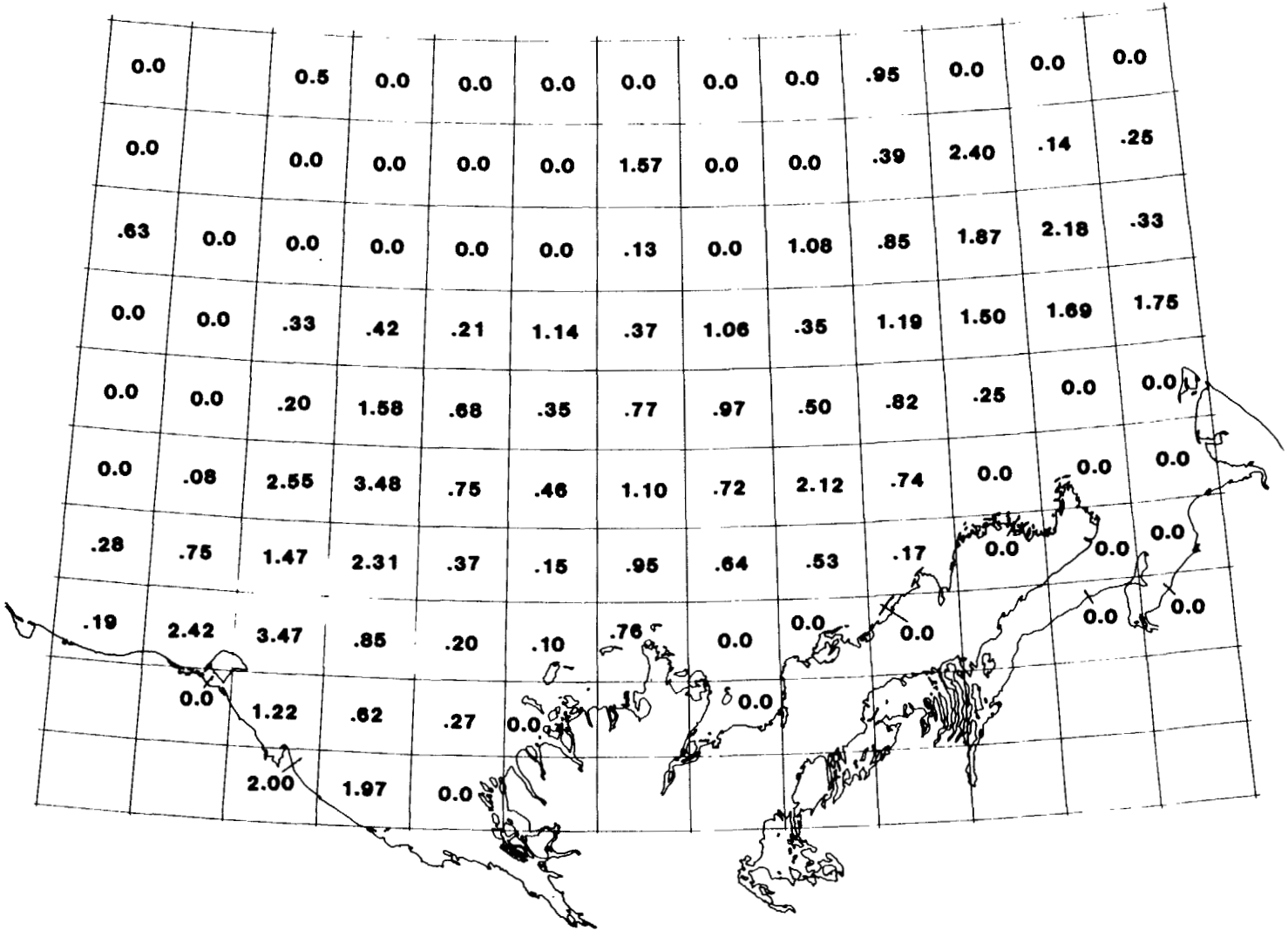


FIGURE 7: AVERAGE RELATIVE DENSITY OF BOWHEAD WHALES BY SUBAREA.

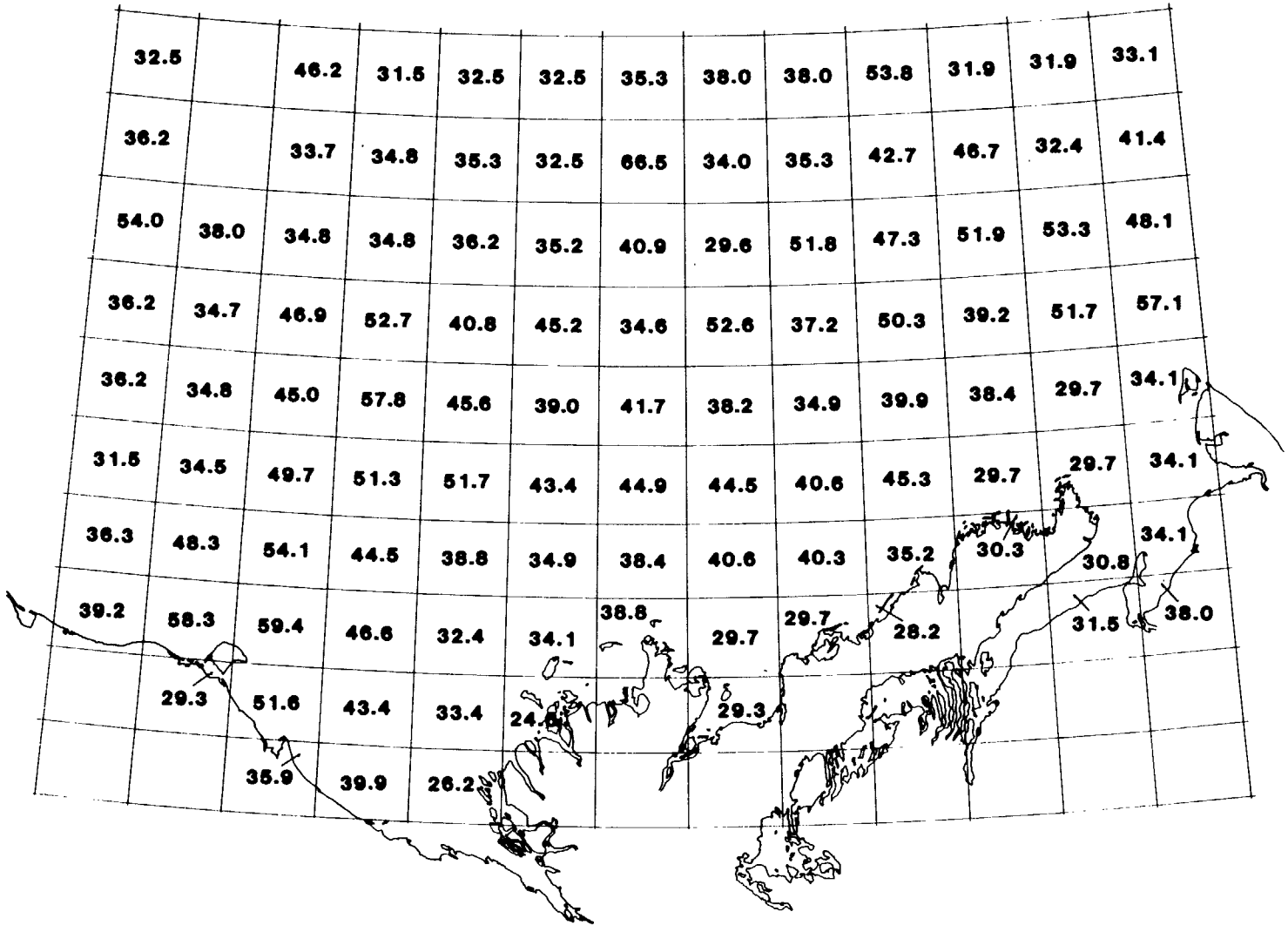


FIGURE 8: AVERAGE RANKED BOWHEAD WHALE DENSITIES, ALL SURVEYS.

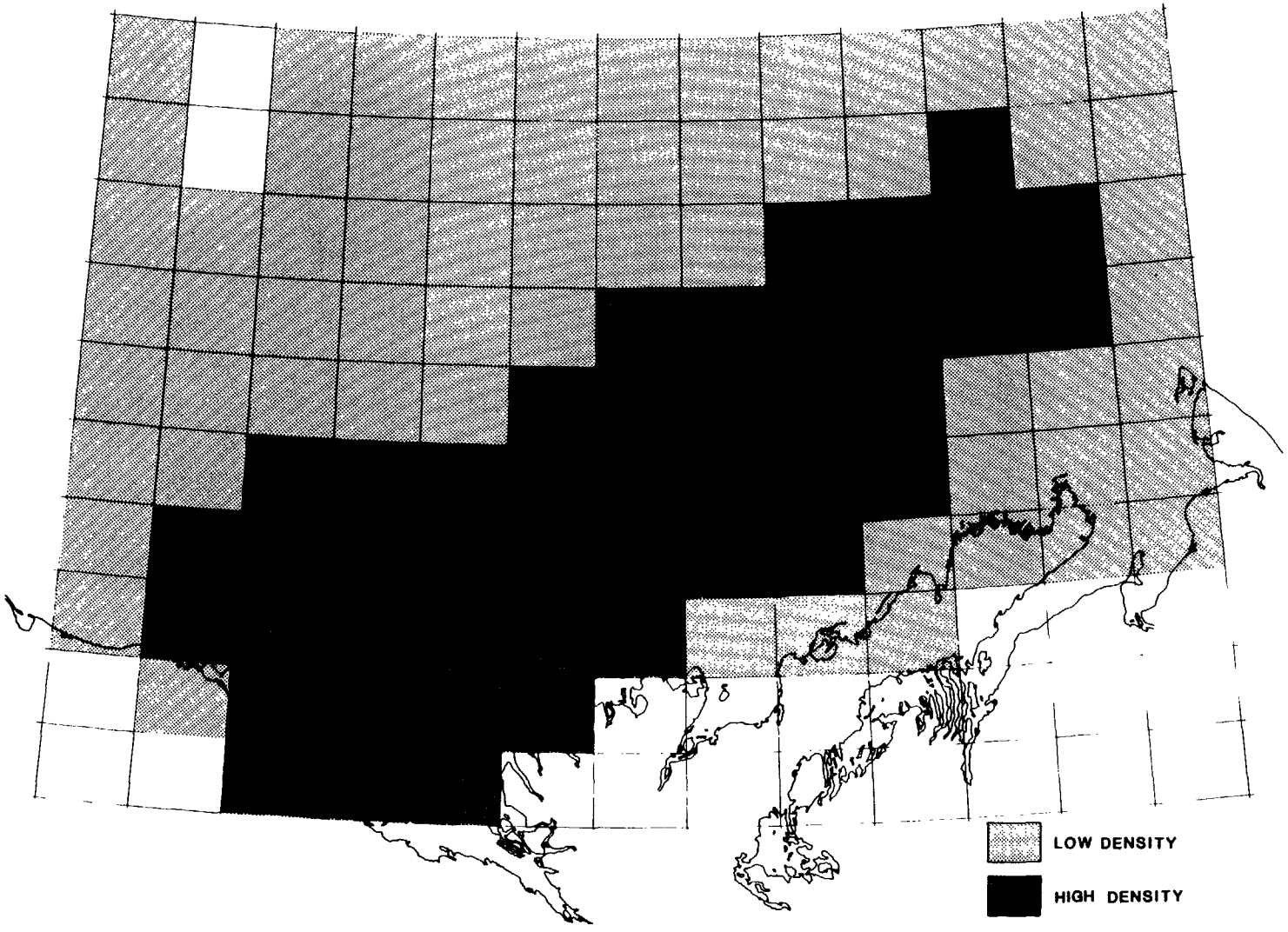


FIGURE 9: CLUSTERING PATTERN OF RANKED BOWHEAD WHALE DENSITIES, ALL EIGHT (8) SURVEYS - 2 STRATA.

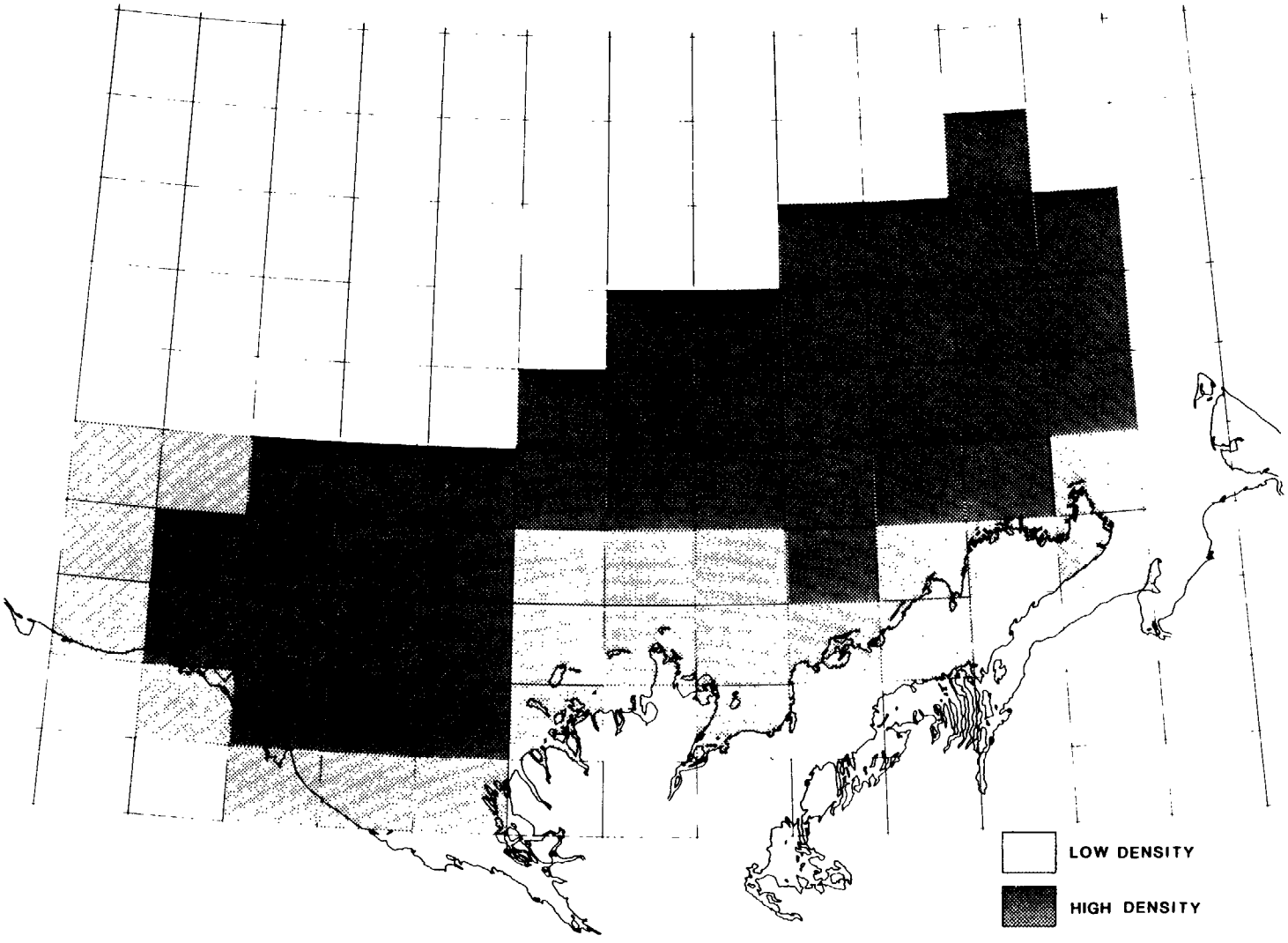


FIGURE 10: CLUSTERING PATTERN OF RANKED BOWHEAD WHALE DENSITIES LEAVING OUT 1981 SURVEYS 2 STRATA

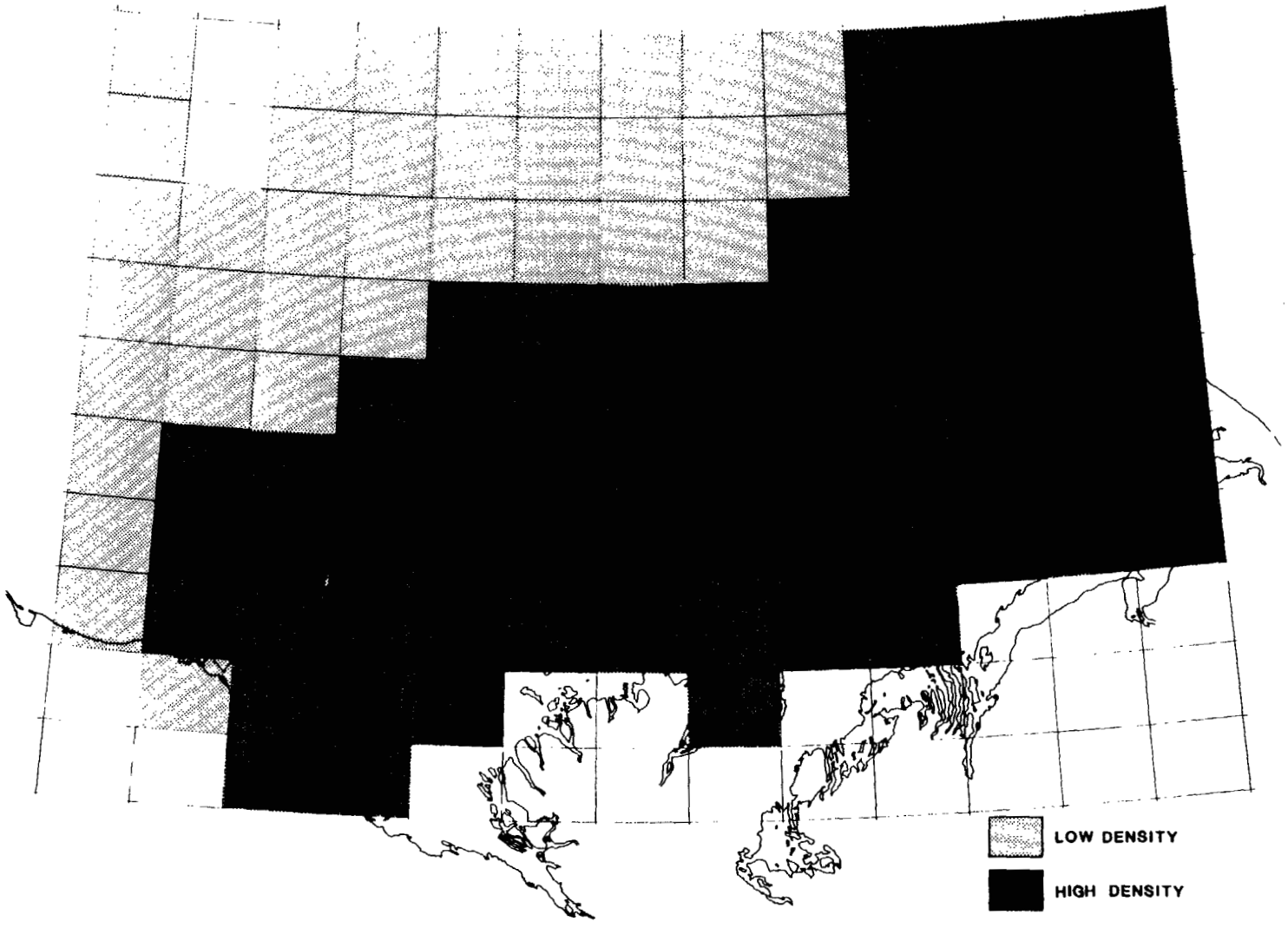


FIGURE 11: CLUSTERING PATTERN OF RANKED BOWHEAD WHALE DENSITIES. LEAVING OUT 1982 SURVEYS - 2 STRATA.

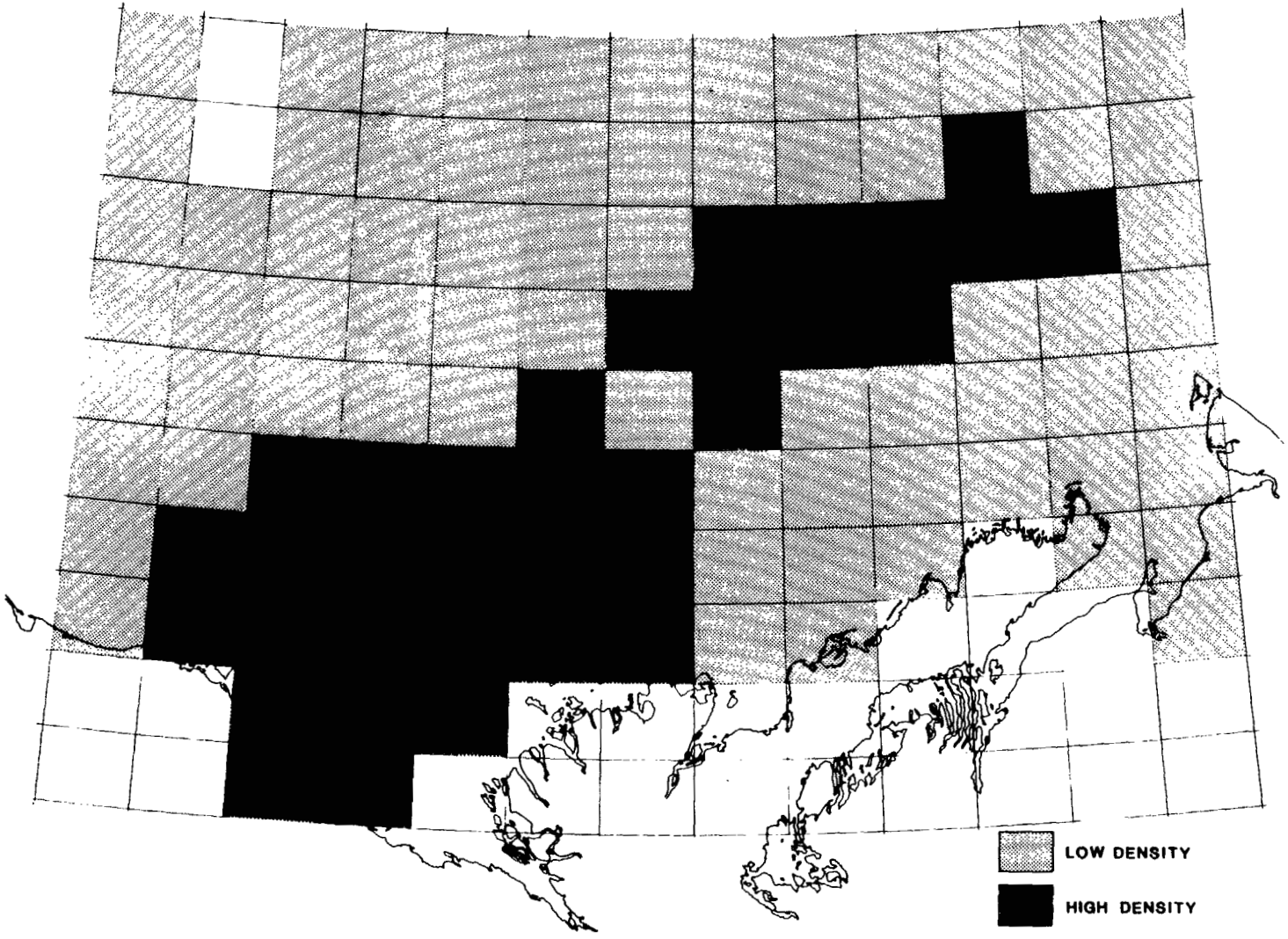


FIGURE 12: CLUSTERING PATTERN OF RANKED BOWHEAD WHALE DENSITIES, LEAVING OUT 1983 SURVEYS - 2 STRATA.

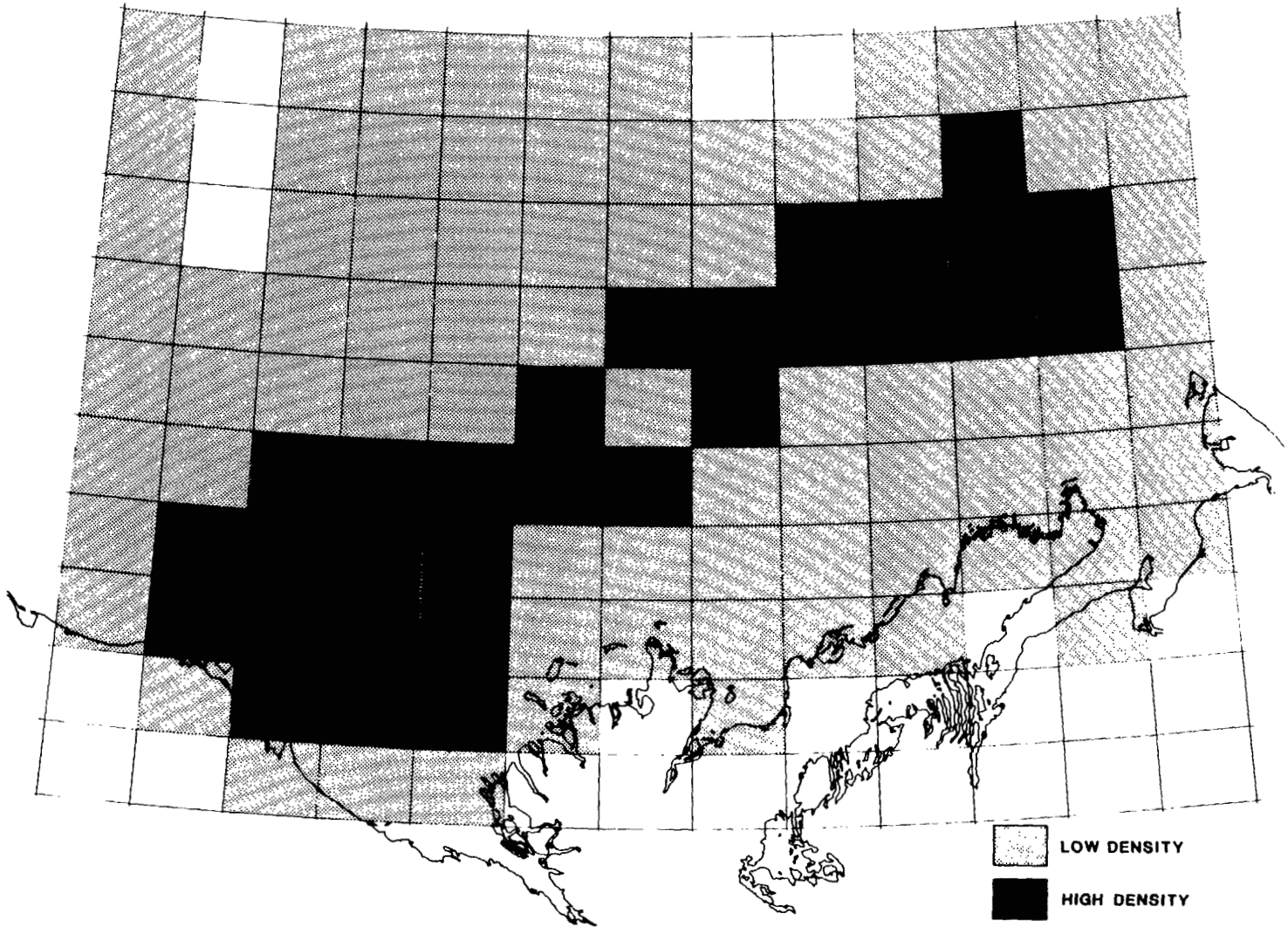


FIGURE 13: CLUSTERING PATTERN OF RANKED BOWHEAD WHALE DENSITIES, LEAVING OUT 1984 SURVEYS - 2 STRATA.

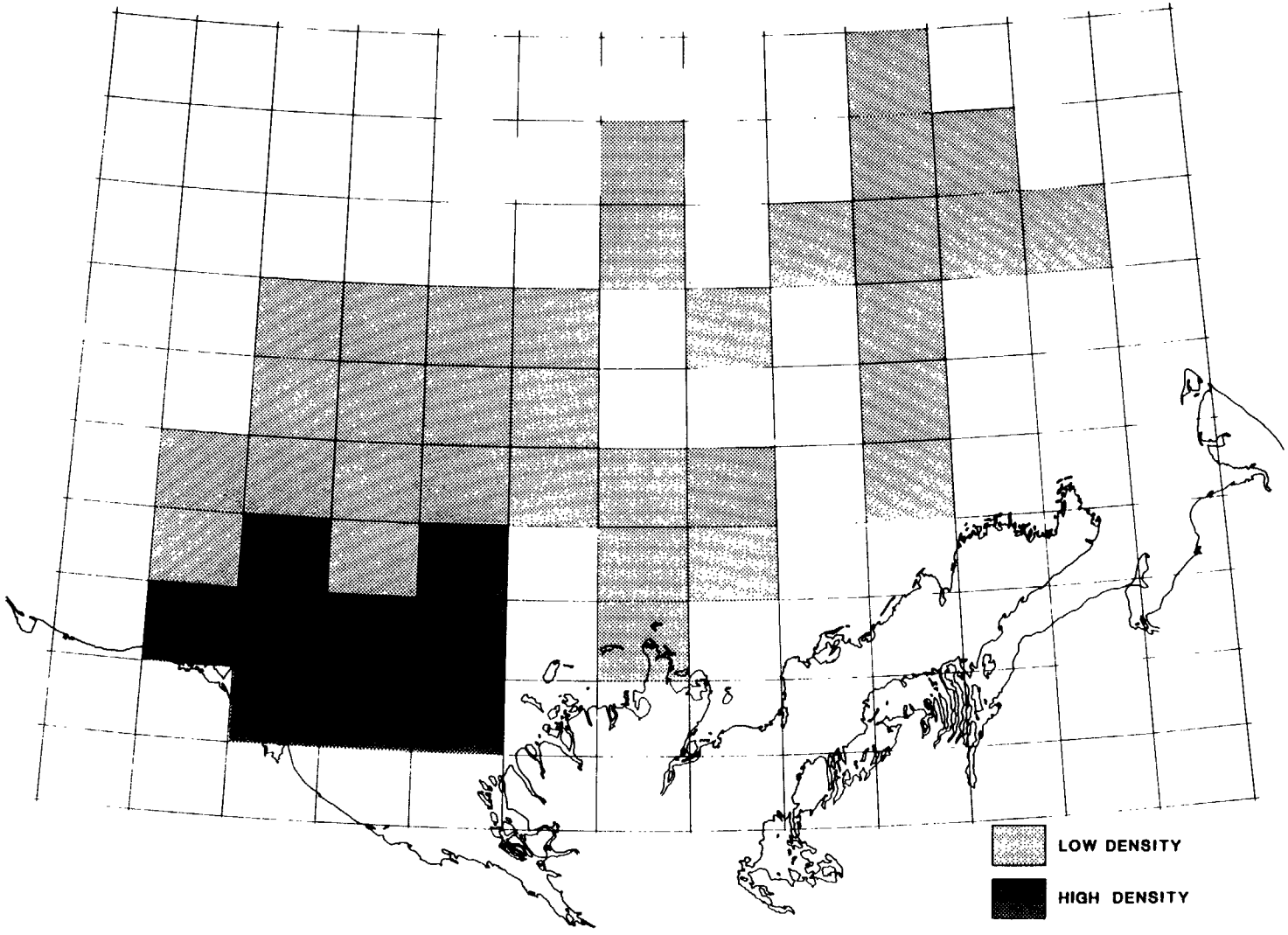


FIGURE 14: CLUSTERING PATTERN OF RANKED BOWHEAD WHALE DENSITIES, EARLY (AUGUST) SURVEYS - 2 STRATA.

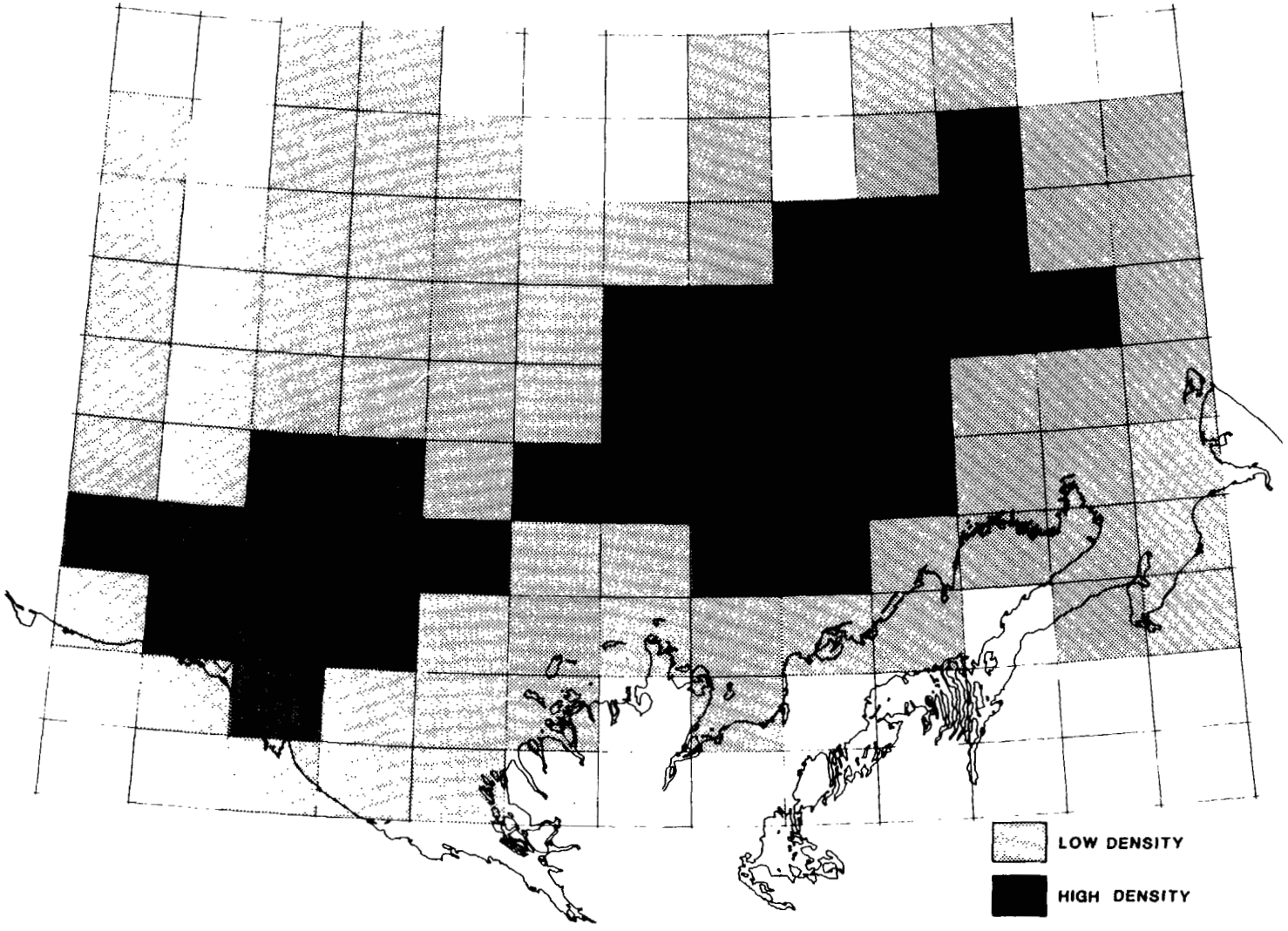


FIGURE 15: CLUSTERING PATTERN OF RANKED BOWHEAD WHALE DENSITIES, LATE (SEPTEMBER) SURVEYS 2 STRATA.

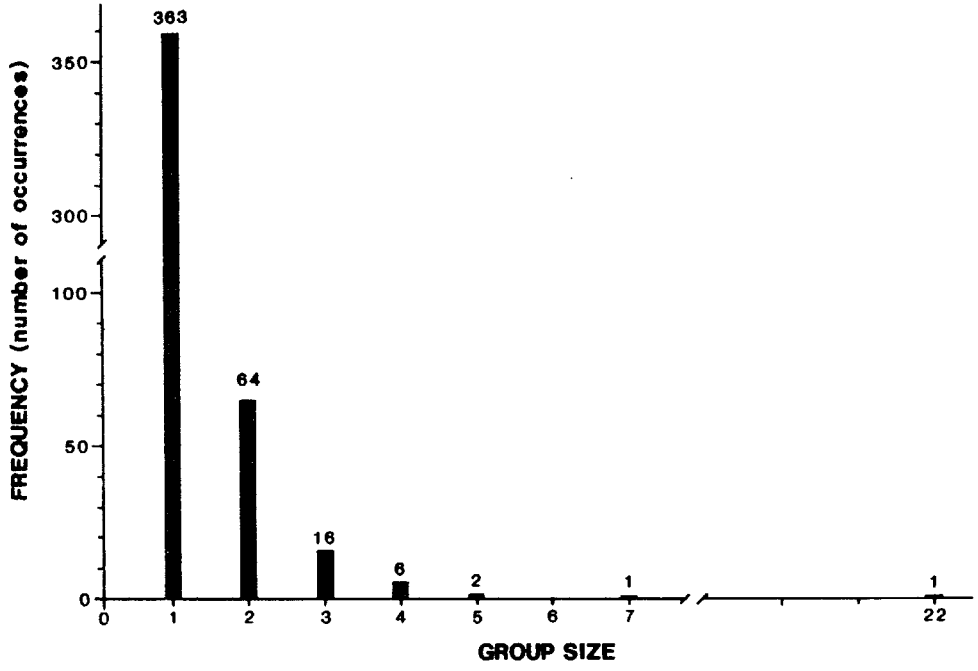
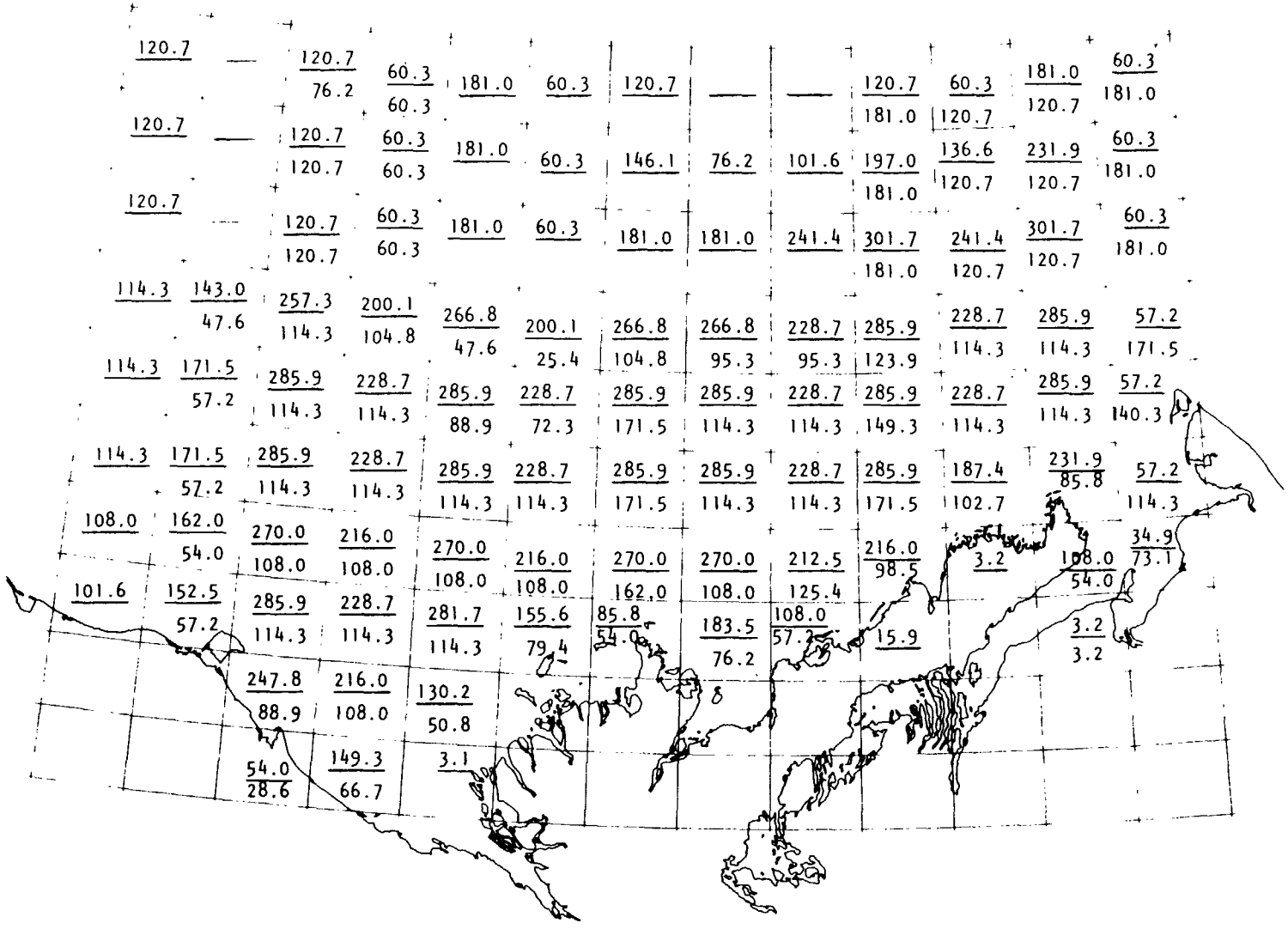
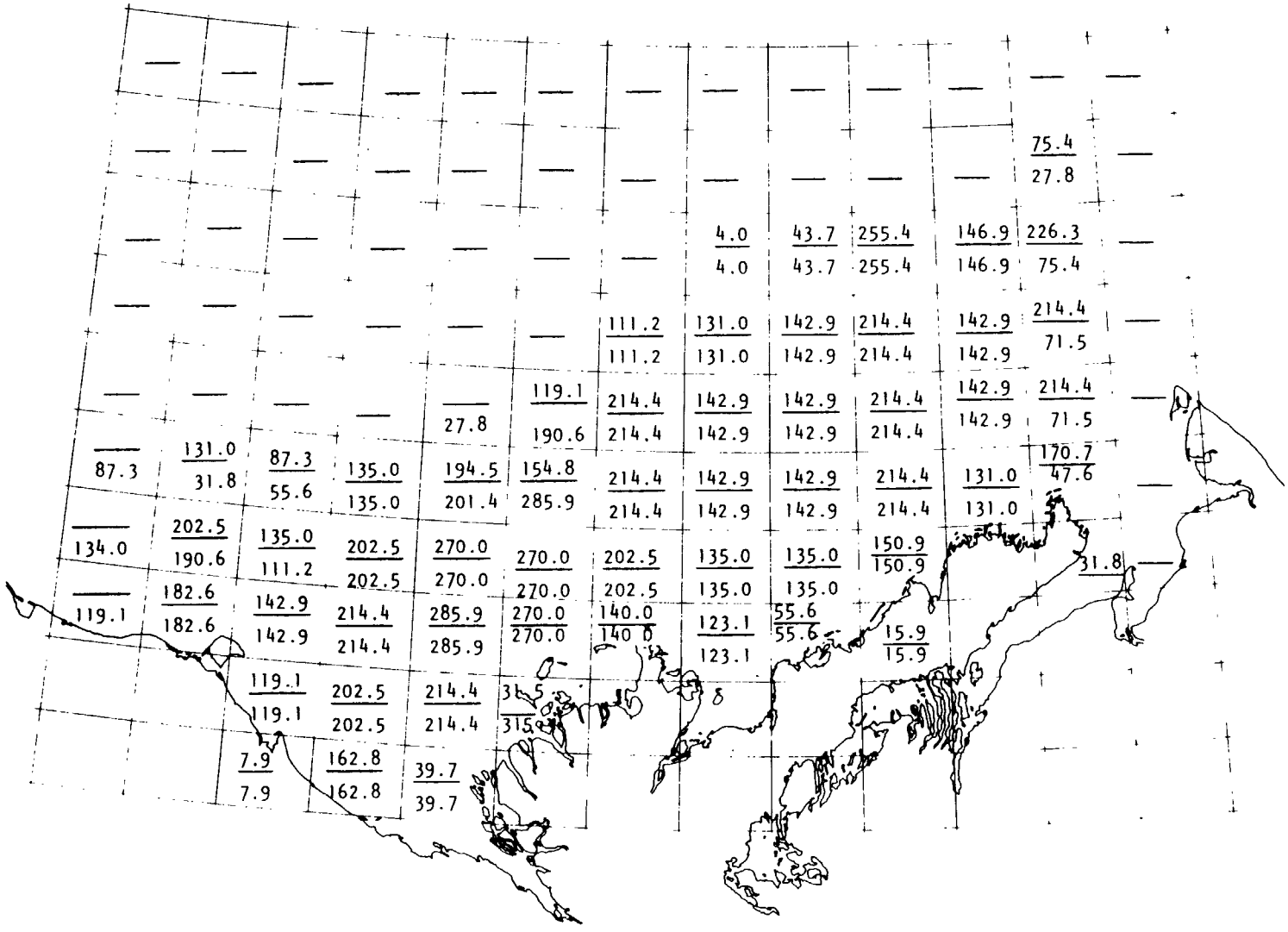


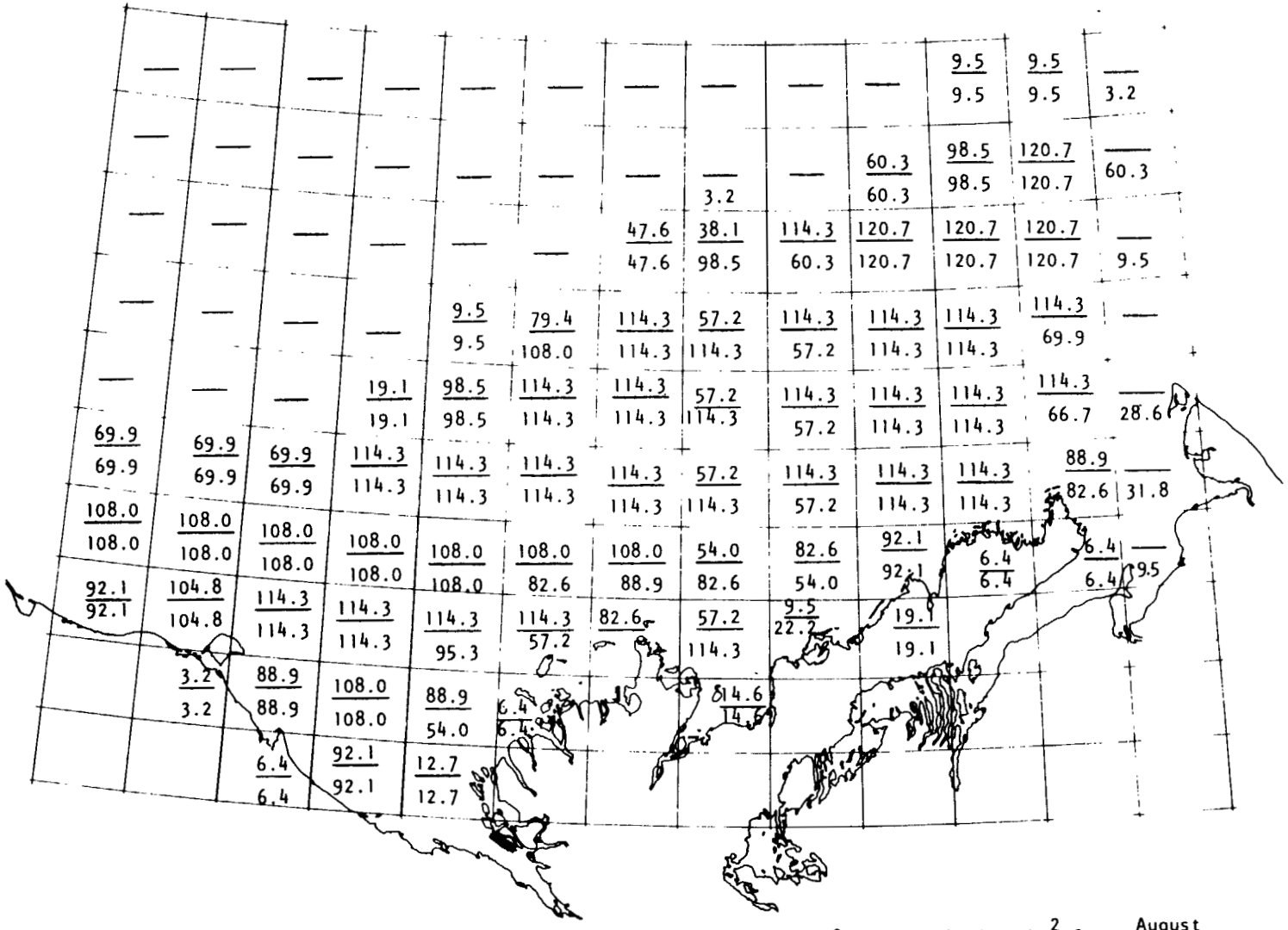
FIGURE 16: BOWHEAD WHALE GROUP SIZE FREQUENCY DISTRIBUTION, BASED ON AERIAL SURVEYS 1981-1984



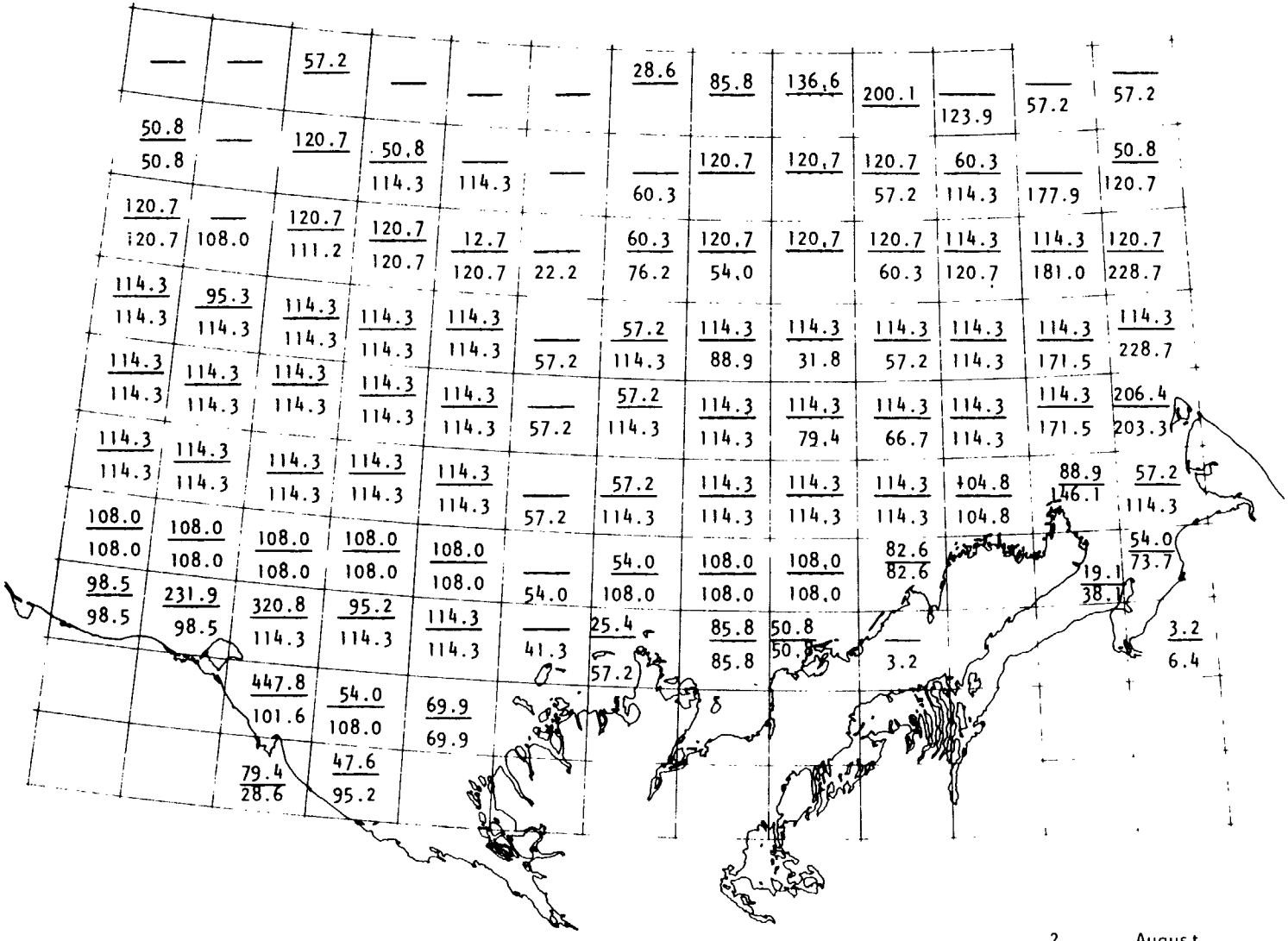
Appendix A. Survey coverage, bowhead whale monitoring project, 1981. Quantified as km^2 for $\frac{\text{August}}{\text{September}}$



Appendix B. Survey coverage, bowhead whale monitoring project, 1982. Quantified as km^2 for $\frac{\text{August}}{\text{September}}$



Appendix C. Survey coverage, bowhead whale monitoring project, 1983. Quantified as km^2 for $\frac{\text{August}}{\text{September}}$



Appendix D. Survey coverage, bowhead whale monitoring project, 1984. Quantified as km^2 for $\frac{\text{August}}{\text{September}}$