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ESTIMATION OF DENSITY OF DOLPHIN SCHOOLS IN THE EASTERN TROPICAL PACIFIC OCEAN USING LINE TRANSECT METHODS

by

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ABSTRACT

Aerial and research ship surveys were conducted from 1977 through 1983 to provide data to estimate density of dolphin schools in the eastern tropical Pacific. Line transect theory was used to compute estimates. Several assumptions of line transect theory were investigated for both aerial and ship data. Correction factors were developed to help accommodate violations of the assumptions. Estimates are presented for data stratified into an inshore area surveyed by planes and an offshore area surveyed by ships. These estimates were combined to determined density for the entire area. Densities for the inshore, offshore and all areas were 4.18, 2.04, and 2.71 schools/1000 km^2, respectively. Maximum adjustments for possible biases due to adverse sea state and sun glare conditions increased the inshore estimate by 76% and the offshore estimate by 64%; however, these adjustments were based upon assumptions which were likely violated.

INTRODUCTION

The National Marine Fisheries Service (NMFS) has been asked to assess the status of dolphin stocks subject to being taken incidentally by tuna purse seiners in the Eastern Tropical Pacific (ETP). Techniques used by NMFS to assess these stocks (Smith 1979)[1] require determining their population sizes. Previous population estimates were made in 1975 (Smith 1975)[2] and in 1979 (Holt and Powers 1982).

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[1]Smith, T. 1979. Report of the status of porpoise stocks workshop (Aug. 27-31, 1979) Southwest Fish. Cent. Adm. Rep. No. LJ-79-41, La Jolla, CA.120 pp.

[2]Smith, T. 1975. Estimates of sizes of two populations of porpoise (Stenella) in the eastern tropical Pacific Ocean. Southwest Fish. Cent. Adm. Rep. No. LJ-75-65. La Jolla, CA. 88 pp.

Since 1979, NMFS has collected additional information to test the assumptions of its statistical methods and to further survey the areas inhabited by the dolphins. In this paper I will discuss data collected from 1977 through 1983 and present density estimates of dolphin schools in the ETP.

MATERIAL AND METHODS

Surveys

Data for calculating the density of dolphin schools were collected during several years. Aerial surveys were conducted in 1977 and 1979 (Figure 1) and research ship surveys were made in 1977, 1979, 1980, 1982, and 1983 (Figure 2). All surveys were conducted between January and early April except an additional ship survey was made in October, 1977 and two cruises were made from May through August, 1980.

Two airplanes were used during the 1977 aerial survey: a P2V Neptune antisubmarine patrol bomber and a two engine PBY amphibian patrol bomber (SWFC 1978)[3]. In the 1979 aerial survey, a four engine PBY bomber was used (Jackson 1980)[4].

Operating and viewing conditions aboard the three aircraft varied greatly (SWFC 1978[3], Jackson 1980[4]). The P2V maintained a cruising speed of 268-370 km/hr (145-200 knots) and lacked bubble shaped waist viewing windows. The entire nose of the P2V was plexiglass, from which the bow observer had an excellent forward, lateral, and downward view. The two PBYs cruised at 148-240 km/hr (80-130 knots) and had bubble shaped waist windows. The 1977 PBY had an isosceles-trapezoidal-shaped flat bow window, and the 1979 PBY had a round bubble-shaped bow window. The round bubble window allowed better lateral viewing, but both provided unobstructed forward and downward views.

Two research vessels were used to collect the shipboard data: R/V _David Starr Jordan_ was used during all years, and R/V _Townsend Cromwell_ joined it in 1977, 1979, and 1980. Viewing conditions differed aboard the two research ships. The _Jordan_ is 52 m long and can maintain a cruise speed of 18.5 km/hr. Binoculars, used to locate animals, were mounted on the upper deck approximately 10.7 m above the sea. The _Cromwell_ is 50 m long and can also cruise at 18.5 km/hr. Binoculars on the _Cromwell_ were located only 6.1 m above the sea. Observers aboard the _Jordan_ used 20X binoculars during the 1977 surveys but thereafter used 25X glasses; observers aboard the _Cromwell_ used 20X glasses. Viewing conditions were generally considered much better on the larger, more stable _Jordan_.

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[3]SWFC (Southwest Fisheries Center, Nat'l Mar. Fish. Serv., NOAA, La Jolla, CA 92038). 1978. Aerial survey trip report, January-June. 1977. Southwest Fish. Cent. Adm. Rep. No. LJ-78-01. La Jolla, CA. 73 pp.

[4]Jackson, T. 1980. Trip Report: Porpoise population aerial survey of the eastern tropical Pacific Ocean, January 22-April 25, 1979, Southwest Fish. Cent. Adm. Rep. No. LJ-80-01, La Jolla, CA. 74 pp.

Study Area

Survey efforts traversed the composite range of ETP dolphin stocks defined by Au et al. (1979)[5]. The total range (Figure 1) was partitioned into "inshore" and "offshore" areas. Within the inshore area, a "calibration" area was defined to compare aerial and ship data both within and among survey years. Surveys were conducted throughout the total range and, except for the 1977 ship surveys, had concentrated annual effort in the calibration area.

Data Collection

Data collecting procedures used during the aerial surveys are described by SWFC (1978)[3], Jackson (1980)[4], Cologne and Holt (1984)[6], and Holt and Powers (1982). Shipboard collection procedures are described in the various cruise reports (unpublished documents available from the SWFC) and by Holt (1983a). Only details specifically relevant to these analyses are reiterated here.

Aerial Data--The airplanes traversed predetermined tracklines (Figure 1) while schools on and to either side of the lines were recorded. Observers searched through the bow window and from waist windows located on either side of the plane. The bow observer was responsible for detecting schools on the trackline (a path underneath the plane 0.19 km wide). He was instructed to terminate the searching mode if environmental or oceanographic conditions restricted his view of the trackline. When possible during the 1979 survey, we observed through a rear port when sun glare on the trackline was a problem. We also stopped searching when the plane was diverted from the trackline for closer examination of a school. Additional schools detected during these diversions were not included in the density analysis.

Environmental conditions recorded during aerial surveys included sea state and sun position relative to the trackline. Sea conditions were measured on the Beaufort scale (Bowditch 1966) and ranged from very flat glossy seas (Beaufort 0 conditions) to rough seas with numerous large, white-capped waves (Beaufort 5 conditions). Effort of greater Beaufort states were omitted from the analyses. Sun location was described by horizontal and vertical position relative to the bow observer (Holt 1983b).

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[5]Au, D., W. Perryman, and W. Perrin. 1979. Dolphin distribution and the relationship to environmental features in the eastern tropical Pacific, Southwest Fish. Cent. Status of Porpoise Stocks working paper SOPS/79/36. La Jolla, CA 59pp.

[6]Cologne, J. and R. Holt. 1984. Observer effects in shipboard sighting surveys of dolphin abundance. Southwest Fish. Cent. Admin. Rpt. LJ-84-30. 42pp.

Biological and physical data for all dolphin species encountered were collected at each sighting (Holt and Powers 1982). Data included species identification, school size estimates, sea state, sun position, and distance of the school from the trackline. Each observer's school size estimates consisted of a "best" estimate plus a minimum and a maximum range.

<u>Ship Data</u>-- Procedures and data recorded on shipboard surveys were similar to those for aerial surveys. Two observers used the 25X binoculars located on each side of the ship to search from directly ahead to directly abeam of their respective sides of the ship. Environmental data recorded included sea state, sun glare, and the presence of fog or rain. Sea state was not recorded during 1977 and during 1979 sea state was not necessarily constant during each effort segment (leg). Sun position was recorded only during the 1982 and 1983 ship surveys.

The bearing (θ) and radial distance (r) of a school from the ship was recorded, and perpendicular distance (y) was then calculated as $y = r \sin \theta$. During the 1977 and 1979 surveys observers rounded estimates of sighting angles to multiples of 5° or 10°, and radial distances to multiples of 185 m (0.1 nm) within the first 1.85 km (1 nm), and to 0.93 km (0.5 nm) multiples at larger distances (Figure 3). Prior to the 1980 survey, observers were aware of inaccuracies but were unable to make precise visual estimates of angles and distances for schools recorded at great distances from the ship (Figure 3). During the 1982 and 1983 surveys, estimates of bearing were recorded using a 360° graduated washer attached to the base of the binoculars, and the radial distances were measured using a graduated reticle enclosed in the right eyepiece of the binoculars (Holt 1983a). With this system, the rounding to convenient values was further reduced (Figure 3); however, the accuracy of the measurements may still be poor.

Analytical Methods

Line transect (LT) theory has been used to estimate density for many terrestrial species (Robinette et al. 1954; Gates et al. 1968) and for dolphins (Leatherwood et al 1978; Smith 1981; Holt and Powers 1982). Density estimates are made using appropriate statistical models accounting for the distances from the trackline at which objects are seen (Burnham et al. 1980). LT theory assumes that dolphin schools (recorded as points) are distributed in the ETP according to some stochastic process with rate parameter D (density of schools per unit area) (Burnham et al. 1980). In the basic equation (Seber 1973),

$$D = \frac{nf(0)}{2L}$$

n is the number of schools sighted, $\hat{D}$ is the density of dolphin schools per km^2, L is the total linear distance searched (km) and f(0) is a probability density function (pdf) evaluated at perpendicular distance, x=0. Burnham and Anderson (1976) show that a pdf, say f(x), can be defined for any continuous detection function, g(x), where g(x) is the probability of observing a dolphin school given it is x perpendicular distance from the line.

Hence, the critical factor is one of estimating f(0). Given an estimate of $\hat{f}(0)$, density is estimated as

$$\hat{D} = \frac{n\hat{f}(0)}{2L} \tag{1}$$

The asymptotic sampling variance of $\hat{D}$ can be estimated (Burnham et al. 1980) as

$$\hat{V}ar(\hat{D}) = \hat{D}^2 \left[\frac{(\hat{v}ar(n)}{n^2} + \frac{\hat{v}ar(\hat{f}(0))}{(\hat{f}(0))^2} \right] \tag{2}$$

where $\hat{v}ar(\hat{f}(0))$ is dependent upon the specific model chosen, and $\hat{V}ar(n)$ is determined empirically using systematically replicated flights or days for plane or ship data, respectively. $\hat{V}ar(n)$ is computed as

$$\hat{V}ar(n) = \frac{L}{R-1} \left[\sum_{i=1}^{R} l_i \left(\frac{n_i}{l_i} - \frac{n}{L} \right) \right]^2 \tag{3}$$

where R = number of lines surveyed, l_i = km searched on ith line, n_i = number of schools observed on ith line, L = total km searched on all lines, and n = total number of schools observed on all lines.

Models for estimating f(0) that incorporate perpendicular distance data grouped in frequency intervals, such as the dolphin survey data, have only recently become available (Burnham et al. 1980; Pollock 1978; Crain et al. 1978). The nonparametric Fourier series (FS) (Crain et al. 1978) was selected for this analysis based upon criteria developed by Burnham et al. (1979). The reader is referred to Burnham et al.'s monograph for a full presentation of the FS model.

Several assumptions must be met for valid use of LT theory, and I investigated three of them for this study: (1) schools directly on the trackline are never missed, (2) schools do not move in response to the approaching ship or plane; and (3) no systematic measurement errors occur. All three assumptions have been made in analyzing previous aerial survey data (Holt and Powers 1982); however, detection of on-track schools may have been influenced by sea state, sun glare, and observer performance (Holt 1983b). Au and Perryman (1981) indicated that dolphins in the ETP may exhibit an avoidance behavior toward approaching ships (threatening assumption 2); however, recent work indicates that ETP dolphins are usually detected before they exhibit an avoidance behavior (Hewitt ms.)[7]. In addition, because of rounding errors already discussed, an inordinately high number of schools detected from the ships were recorded on the trackline (failure to meet assumption 3). Therefore, LT theory could not be applied directly to the ship survey data.

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[7]Hewitt, R. ms. Reaction of dolphins to a survey vessel: effects on census data.

Instead, I adjusted ship data in two ways; first, I "corrected" data inaccuracies and then applied LT methods (termed LT method). Secondly, I calculated several relative abundance indices and then computed a correction factor to adjust the relative indices to obtain absolute density estimates. The correction factor (C) was the ratio of absolute density from plane data to the relative ship index in the calibration area,

$$C = \frac{\hat{D}_p}{g}. \qquad (4)$$

The absolute density estimate for a specified area (offshore, inshore or total area) was

$$\hat{D}_s = C * h$$

or

$$\hat{D}_s = \frac{\hat{D}_p}{g} * h \qquad (5)$$

where $\hat{D}_s$ = absolute density estimate of schools in some specified area, (offshore, inshore, or total area),

$\hat{D}_p$ = density estimate of schools in the calibration area based on plane data,

g = relative abundance index calculated for ship data in the calibration area, and

h = relative abundance index calculated for ship data in the specified area.

The sampling variance of $\hat{D}_s$ is approximated by Taylor series expansion (Seber 1973) as

$$\hat{Var}(\hat{D}_s) = \hat{D}_s^{\,2}\left[(cv(\hat{D}_p))^2 + (cv(h))^2 + (cv(g))^2 \right] \qquad (6)$$

The asymptotic sampling variance of $\hat{D}_p$ is given by equation (2) and the variances for the g and h terms are dependent upon the specific index chosen.

I calculated two different indices of relative abundance for the g and h terms using ship data. One was a simple ratio of the number of sightings per track searched, expressed as schools/1000 km searched. For the second index, I assumed that the estimate of school density using equation (1), expressed as schools/1000 km^2, was a relative index. I call the two indices "detection rate" and "relative density", respectively.

In equation 5 the indices used for the g and h terms do not depend upon the assumptions of LT theory, but they may be affected by changes in sighting conditions, such as weather conditions or by survey platform effects. Therefore, I calculated indices for sea state categories (defined below) stratified by vessel where adequate data were available. Where adequate data were not available, I used the unstratified data. I calculated a combined absolute density estimate pooled over all strata in the specified area ($\hat{D}_c$) by weighting each stratum by the respective track searched as

$$\hat{D}_c = \frac{\sum_{i=1}^{2} \sum_{j=1}^{2} (\hat{D}_s)_{ij} (L_s)_{ij}}{\sum_{i=j}^{2} \sum_{j=1}^{2} (L_s)_{ij}} \qquad (7)$$

where

$\hat{D}_s$ = estimated density in the specified area based on data for the ith sea state category (described below) and by the jth ship,

$(L_s)_{ij}$ = track searched in the specified area during the ith sea state category and by the jth ship.

The sample variance is given by

$$\mathrm{Var}(\hat{D}_c) = \frac{\sum_{i=1}^{2} \sum_{j=1}^{2} ((L_s)_{ij})^2 \mathrm{Var}(\hat{D}_s)_{ij}}{\left(\sum_{i=1}^{2} \sum_{j=1}^{2} (L_s)_{ij} \right)^2}$$

I determined the correction factor (C), equation 4, using the ratio of the 1979 aerial survey density estimates, stratified by sea state category, to the 1979 Jordan and Cromwell data, each stratifed by sea state category. I calculated absolute density estimates using equations 5 and 7 for the offshore, inshore and total areas. An example application of equations 5 and 7 to determine the offshore density estimate using 2.13 km truncated data is in Appendix 1.

Data Treatment

All species of dolphins encountered in the study area were included in the analyses. Of these, only schools with a mean minimum or mean best estimate of greater than 14 animals were used because, the probability that all animals in a school of at least this size would be submerged at one time, and hence undetectable, was virtually zero.

During all but the last two flights of the 1979 aerial survey, two independent teams of three observers each searched for dolphin schools. Members of a team always observed from the bow, left and right windows at the same time, alternating with the other team. Two of the original observers were replaced by another observer during the last two flights. Five of the observers had participated in the 1977 survey.

During the 1982 and 1983 ship surveys, two independent teams of three observers each were used to search for dolphin schools. One team was experienced in detecting marine mammals from tuna purse seiners (tuna-vessel-experienced:TVE) and one team had similar experience aboard research vessels (research-vessel-experienced: RVE) (Cologne and Holt 1984)[6]. During each survey, the two teams remained independent by alternating searching for dolphin schools. One of the RVE observers participated on both cruises. The number of observers on cruises during the other years ranged from four to seven people and they randomly alternated searching for dolphins.

For aerial and 1979-1983 ship data, sea state conditions were recorded by individual Beaufort but were grouped into (1) a "calm" sea state category-seas without whitecaps (Beaufort conditions 0-2) and (2) a "rough" sea category-seas with whitecaps (Beaufort conditions 3-5). The presence of whitecaps was important because animal splashes were used as sighting cues during calm conditions but could not be used during rough conditions. Because effort during the 1979 ship surveys was not collected in legs with constant Beaufort conditions, effort was equally allocated to each Beaufort category if recorded sea state categories for effort and the associated sightings differed.

For aerial data and 1982-83 ship data, sun glare effects were investigated by classifying sun positions into "good" and "poor" categories defined by sun glare's impact upon the trackline. Criteria used for aerial data were those recommended by Holt (1984)[8]. Criteria used for ship data were based upon observations recorded during a subsequent ship survey (Hohn, personal communication). Poor sun conditions were recorded for ship data only when horizontal sun position was 12 and vertical position was 1, 2, or 3 or when there were clouds together with fog or rain.

It was suspected that the 1977 aerial observers' ability to detect dolphin schools, both on and off the trackline, from the P2V aircraft may have been hampered by cruising speeds over 370 km/hr. The slower PBY averaged approximately 220 km/hr (SWFC 1978)[3]. I compared the rates at which observers detected schools on and off the trackline from the two planes. To eliminate spatial effects, I compared only searching effort of the other aircraft (Figure 4).

Detection rates of trackline schools and all schools were smaller for the P2V data than for the PBY data (Figure 5). Stratifying the two data sets to account for sea state or sun glare reflected the same trend. Therefore, I did not use the P2V data in the density analyses.

In order to apply the FS model to the data, I made several somewhat subjective decisions regarding the structure of the data. These included selecting appropriate interval widths for grouping the perpendicular sighting distributions (data cutpoints), choosing a maximum observation distance (w) perpendicular to the trackline (truncation point), developing criteria to select the appropriate number of terms for the FS model, and choosing the type of transformation to use in compensating for measurement error in the shipboard data.

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[8]Holt, R.S. 1984. Testing the validity of line transect theory to estimate density of dolphin schools. Southwest Fish. Cent. Admin. Rept. LJ-84-31. 56pp.

Aerial Data Model Application

On the basis of previous research (Holt and Powers 1982), I selected a truncation point of 1.94 km (1.05 nm) and an interval width of 0.19 km (0.1 nm) for the aerial data. I used the "origin" fit method, discussed below, to select the appropriate number of terms in the FS models.

Ship Data Model Application

I investigated the above four techniques for ship data using the 1979, 1980, and 1982 data. I selected these three years because the data had, respectively, large, moderate and small frequency modes in the perpendicular distance distributions at the origin (Figure 3). These three years data provided fits that were representative of other year's data.

Data Smearing-- Although perpendicular distance interval widths of 0.37 km were used to mitigate the observers' inaccuracies in estimating sighting angles and radial distances, a large percentage of the sightings (25% of sightings for data truncated at 3.7 km) were still recorded as being on the trackline. To further reduce these effects, I used a technique of data "smearing" similar to that of Butterworth (1982) and Hammond's method 2 (Hammond In press).

Radial distances (r) and angles Θ were smeared directly using a uniform distribution. Minimum and maximum values of r and Θ between which to smear were determined by $\frac{\Delta r}{2}$ and $\frac{\Delta\Theta}{2}$

such that $r\text{ (smeared)} = r - \frac{\Delta r}{2} + \ell_1 \Delta r$; r(smeared) set to 0 if less than 0

and $\Theta\text{(smeared)} = \Theta - \frac{\Delta\Theta}{2} + \ell_2\Delta\Theta$

where ℓ_1 and ℓ_2 are random numbers from a uniform {0,1} distribution so that $y \text{ smeared} = r\text{(smeared)} \ \text{Sin} \ |\Theta\text{(smeared)}|$.

I smeared each distribution 200 times and calculated density estimates using the average smeared perpendicular distance distribution. I determined the value of $\frac{\Delta r}{2}$ by the estimated radial distance.

If $r<0.5, \frac{\Delta r}{2} = 0.05$; if $0.5<r<2.0$, $\frac{\Delta r}{2} = 0.25$; and if $r>2.0, \frac{\Delta r}{2} = 0.5$.

If r(min)<0.0, r(min) was set equal 0.0. The value of $\frac{\Delta\Theta}{2}$ was equal 7.5° based upon recent IWC/IDCR Minke whale data analyses (Hammond, Pers Comm).

As expected, smearing the spiked 1979 data reduced the number of sightings recorded as being on the trackline (Figure 6). Some of these sightings no longer fell within the first perpendicular distance interval. The reduction at the origin was less for the 1980 data and the greatest effect on the 1982 data occurred in the "tail" region of the sighting distribution.

The density estimate for the 1979 data was smaller with the smeared data than with the unsmeared data (Figure 7). This reflects the reduced spike at the origin in the smeared sighting distribution. The smeared data required fewer terms in the FS model for the 1979 and 1982 data but an additional term for the 1980 data. Because of the apparent errors in recording the data for all years, I used the smearing technique to analyze all ship data, including the following comparisons.

Term Selection-- Criteria have been developed to objectively select the number of terms, m, in the FS model. Burnham et al. (1980) describe two techniques: (1) the log likelihood ratio (LLR) test, which compares log-likelihood values between the m and m+1 term models, and (2) a "stopping" rule (SR) where m is chosen such that

$$\left(\frac{1}{w}\right)\left(\frac{2}{(n+1)}\right)^{1/2} \geq |\hat{a}_{m+1}|$$

where $|\hat{a}_{m+1}|$ is the absolute value of $|\hat{a}_{m+1}|$

I examined two additional, more empirical methods of selecting m. One was simply to select the model that most closely fit the pdf at the origin (first few intervals- termed origin fit); the second, similar method used the maximum overall chi-square-goodness-of-fit probability value to select the model with the best overall fit (termed chi-square fit).

The LLR test for the 1979, 1980, and 1982 data selected models with the fewest terms and resulted in the lowest estimates of school density (Figure 8). However, models selected by the LLR test fit the spiked distributions poorly (Figure 9). The SR test selected the same number of terms as did the chi-square test for the 1979 and 1980 data and selected the same number terms as the LLR test for the 1982 data. Although I used critical test values to compare m and m+1 term models for the LLR and SR tests, selection of the appropriate number of terms was frequently subjective because the calculated value to be compared may have been very close to the test value.

Use of the chi-square test may also be subjective because chi-square probability values for models with greatly different number of terms were occasionally similar. However, the estimate of school density for the model with the larger number of terms was usually much larger than the estimate for the smaller termed model. Also for some data sets, the chi-square probability values for all models, regardless of the number of terms, were very low ($P<0.001$) or were very high ($P>0.99$), which made selecting the appropriate model difficult.

The application of the origin fit method was most consistent. It was easily applied by visual inspection of the calculated pdf. By definition, it provided the best fit to the spike near the origin. It generally resulted in the selection of more terms than did the other criteria and hence the values of $\hat{f}(0)$ tended to be larger for the spiked data (Figure 8). The method assumed that the spikes' relative sizes at the origin in the perpendicular distance distributions in the calibration area and in the area for which density was being estimated indicated relative densities among the data sets, i.e., that the same factors that caused the data spikes operated consistently between the two areas. Because the absolute density estimate was calculated as a ratio of relative indices (Equation 5), the consistency of selecting terms was more important than the absolute size of the individual estimates. Therefore, I used the origin fit method to select the appropriate number of terms for the ship data.

Data Truncation--The data analysis should include the largest number of sightings possible. However, schools detected at extreme perpendicular distances from the trackline have minimal impact on the density estimates; in fact, estimation models may better fit the data with these schools removed. From the ships, a few schools were detected further than 18 km perpendicular to the trackline, but 97% of all schools were detected within 7.4 km (4.0 nm) of the trackline. In addition, 82% of all schools were detected within 3.7 km (2.0 nm), and 64% within 2.1 km (1.15 nm) of the trackline.

I truncated the ship data at 7.4, 3.7, and 2.1 km and examined the effects on the density estimates for the 1979, 1980, and 1982 smeared data. The 7.4-km truncated data yielded a poor fit (Figure 10), and the estimates of school density were less than for the data truncated at 3.7 and 2.1 km (Figure 11). The pdf for models with more than four terms tended to oscillate in the extreme tail region. A 2.1-km truncation point yielded estimates similar to the 3.7-km truncated data but it excluded 36% of the data. Furthermore, sufficient degrees of freedom to calculate the chi-square test existed only for the first 4-term models (using a grouping interval width of 0.37 km as discussed below). Because a 3.7-km truncation point provided a suitable fit to the data and only required exclusion of 18% of the data, it was used as the truncation point.

Interval Widths-- Perpendicular distances for ship sightings were grouped into intervals using two width categories. One classification used interval widths of 0.19 km (0.1 nm), which corresponded to the widths used for aerial data. The first interval was only 0.09 km (0.05 nm) wide. Cutpoints used were 0.09, 0.28, 0.46, 0.65, 0.83, 1.02, 1.20, 1.39, 1.57, 1.76, 1.94, 2.13, 2.31, 2.78, 3.24, and 3.70 km. The second classification used interval widths of 0.37 km (0.2 nm). The first interval was only 0.28 km (0.15 nm) wide. Cutpoints were 0.28, 0.65, 1.02, 1.39, 1.76, 2.13, 2.31, 2.78, 3.24, and 3.70 km.

The FS provided good fits to the smeared distributions of both interval widths for all three years' data (Figure 12). The 0.19 km widths required substantially more terms in the models than did the 0.37 km widths. The additional terms resulted in larger associated variances for the estimates. The coefficient of variations of density for the 1979, 1980, and 1982 0.19-km interval width distributions were 17%, 19%, and 35%, respectively, compared to 14%, 16% and 31% for the 0.37-km width distributions. Pooling the data into the wider intervals reduced the spike near the origin for the 1979 and 1980 data, yielding smaller density estimates (Figure 13). Therefore, since fewer terms in the models were required and variances were smaller, I used interval widths of 0.37 km to analyze the ship data.

RESULTS

Detection of Dolphin Schools

Aerial Data

Density estimates for the 1977 and 1979 aerial data in the inshore area during calm seas or with minimal sun glare were more than twice the estimates during rough seas or poor sun conditions (Table 2). These differences could be attributed to the observers' failure to detect trackline schools during poor conditions, except that the viewing conditions were spatially confounded. This was illustrated by partitioning the inshore aerial data into "coastal" and "offshore" bands for each Beaufort sea state (Figure 14) and sun glare condition (Figure 15).

Sea conditions during the aerial surveys were rougher offshore than nearshore. More searching was done in the coastal band during low Beaufort states, whereas, more searching was done in the offshore band at higher Beaufort states (Figure 14). The rates of detecting dolphin schools were higher at each Beaufort state in the coastal band than in the offshore band (Figure 16). The rates of detecting trackline schools were generally higher in the coastal band; however, these rates were based upon very few schools (18 and 10 trackline schools were detected in the coastal and offshore bands, respectively). Lower offshore estimates for data recorded under the same Beaufort state was consistent with a decreasing onshore-offshore density gradient.

Within each band, sea state conditions were also spatially stratified, because the lower Beaufort conditions occurred mostly in the nearshore and northern portions of each band. Predictably, detection rates for all schools within each band declined with increasing Beaufort condition. Because of the large variability inherent in small sample sizes and spatial stratification of searching effort at the various Beaufort conditions, comparisons of rates of detecting trackline schools did not yield consistent trends. For example, within either band, the trackline detection rate for Beaufort 2 conditions was larger than for Beaufort 1 conditions, and in the coastal band Beaufort 5 conditions had higher trackline detection rates than did Beaufort 4 conditions and Beaufort 4 rates were higher than Beaufort 3 rates (Figure 16).

The spatial distribution of searching effort for aerial data during good and poor sun conditions was also confounded with distance from shore (Figure 15) and hence with sea conditions. Most good sun conditions (78%) occurred in the coastal band, whereas 59% of all poor sun conditions occurred in the offshore band. This was because the general searching pattern was to begin searching on the westward, outbound leg in the morning; then to turn the aircraft near noon and reach shore in late afternoon or night. Thus the sun was directly overhead or in front of the plane in the offshore reaches of the track and behind the plane in the nearshore areas.

Detection rates during good and poor sun conditions were higher in the coastal band than in the offshore band (Figure 16), which was consistent with a decreasing density gradient. Within the coastal band, detection rates during good sun condition detection rates were larger than for poor sun conditions, but most of the poor sun data occurred in the westward portion of the band (Figure 15). In the offshore band, trackline detection rates during good and poor sun conditions were similar, but the good sun trackline detection rate was based upon three sightings while searching 2,660 km.

Finally, I examined the performance of the observer teams to test the assumption that all large schools on the trackline were detected. The two teams searched approximately equal proportions of the trackline (Team 1 searched 46% of the effort). No difference in performance of the two teams was evident: their rates of detecting schools, both on and off the trackline, and their estimates of school densities were approximately equal (Figure 17).

Ship Data

The rates of detecting dolphins were greater during calm sea than during rough seas for 1979 through 1983 ship surveys (Figure 18). The detection rate ratios for calm to rough seas were more than 2 to 1. Calm sea to rough sea ratios were larger in the offshore area than in the inshore area.

The offshore area was surveyed during rougher seas than the inshore area: seas were calm in the offshore area during only 17% of the effort as opposed to 35% for the inshore area surveys (Figure 19). The fact that more schools were detected in the inshore area than offshore during either calm or rough seas indicates lower dolphin density offshore. The inshore-to-offshore-area detection ratios were 1.5 during calm seas and 2.0 during rough seas (Figure 18).

Sun glare had little effect on the shipboard observers during the 1982 and 1983 cruises. Poor sun conditions occurred only during 5% of the 1982 and 8% of the 1983 surveys. Rates of detecting schools on the trackline were larger during poor sun conditions than during good conditions in 1982, but no trackline schools were detected when conditions were poor in 1983 (Figure 20). Detection rates during poor sun conditions within 2.1 or 7.4 km of the ship did not indicate adverse sun glare.

The RVE and TVE teams' rates of detecting all dolphin schools were similar in 1982 (Figure 21). The estimate of relative school density for the RVE team's data, however, was more than two-fold greater than the estimate for the TVE team data (Figure 21). This was caused by drastic differences in the teams' distributions of perpendicular sighting distances (Figure 22). The TVE team's distribution increased out to 2.8 km from the trackline. The smaller value of $\hat{f}(0)$ reflected the nondecreasing nature of the distribution.

In 1983, the RVE team's detection rate was 52% greater than the TVE team's rate at a searching width of 7.40 km (4.0 nm), but their rates were very similar within 2.13 km (1.15 nm) (Figure 21). Relative density estimates for the two teams were very similar. Although the TVE team sighted fewer schools than the RVE team, a larger proportion of their sightings was recorded near the trackline (Figure 22), which increased the value of $\hat{f}(0)$ and the density estimate.

Density Estimates

Calibration Area

Aerial Data-- During the 1979 aerial survey, observers detected 56 dolphin schools, including 13 trackline schools, within 1.94 km of the trackline while traversing 10,869 km in the calibration area. The distribution of perpendicular distances is presented in Table 1. A 5-term FS model provided an excellent fit to the 1979 calibration data (Figure 23). The estimate of density was 6.13 schools/1000 km^2 with a standard error of 1.44 (Table 2).

The density estimate for calm sea data was more than three times the estimate for rough sea data in the calibration area (Table 2). The FS models fit both calm and rough sea data poorly (Figure 23). The calm sea distribution had a pronounced spike at the origin but few trackline sightings were made during rough seas. The fit of the calm sea data in the first interval near the origin was less than the calculated pdf; the fit for the rough sea data was greater than the calculated pdf.

Ship Data-- Observers aboard the research vessels in 1979 searched 9,776 km in the calibration area and detected 185 dolphin schools within 7.4 km of the trackline (Table 3). The rates of detection during calm seas were approximately three times the rates in rough seas (Table 3). The same relative trends were found for data truncated at 2.13 km. Rates of detecting schools, either all schools or trackline schools for each sea state category were larger for Jordan observers than for Cromwell observers. The magnitude of difference was less in the rough sea category, especially for data truncated at 7.4 km. Relative density indices for the 1979 calibration area data stratified by each ship and by sea state categories are presented in Table 4.

Inshore Area

Aerial Data-- Aerial observers during the 1977 and 1979 surveys searched 34,006 km and detected 152 dolphin schools in the inshore area (Table 2). The distribution of perpendicular sighting distances are in Table 1. I selected a 9-term FS model (Figure 23); it yielded a density estimate of 4.18 schools/1000 km^2 (Table 2). The fit of the FS model to the calm sea, perpendicular distance data in the first interval was less than the calculated pdf, and the fit to the rough sea data was larger (Figure 23).

Ship Data-- From 1977-1983, shipboard observers searched 27,840 km in the inshore area and detected 460 dolphin schools within 7.4 km of the trackline and 297 schools within 2.13 km of the track (Table 3). A 6-term FS model yielded a LT density estimate for the inshore area of 4.47 schools/1000 km^2 with a standard error of 0.514 (Table 5). This was only slightly larger than the aerial inshore estimate. Each vessel's rates of detecting dolphins in the inshore area during each sea state are presented in Table 3. Absolute density estimates, using equations (5) and (7) and detection rates for shipboard data truncated at 2.13 and 7.4 km, were 6.36 and 6.49 schools/1000 km^2, respectively (Table 5). The relative density indices for ship data stratified by sea state in the inshore area are presented in Table 4. The absolute density estimate, using equations (5) and (7) and relative density estimates, was 6.88 schools/1000 km^2 (Table 5).

Offshore Area

Observers aboard both vessels surveyed 46,567 km in the offshore area and detected 281 dolphin schools within 7.40 km of the trackline and 192 schools within 2.13 km of the trackline (Table 3). Detection rates from the Cromwell were much lower than from the Jordan. The Cromwell, however, searched the most westward range in 1977 and along the equator in 1979; both areas are believed to have low dolphin density. The Jordan searched the central part of the range, an area of suspected high density.

Density estimates calculated with LT methods, detection rates, or relative density estimates for the offshore area were very similar (Table 5). The LT density estimate using a 6-term FS model was 2.04 schools/1000 km^2 with a standard error of 0.263. Absolute density estimates of dolphins in the offshore area using equations (5) and (7) for detection rates with data truncated at 2.13 and 7.40 km were 2.16 and 2.11 schools/1000 km^2, respectively (Table 5). Relative density estimates for ship data in the offshore area are presented in Table 4. The absolute density estimate using equations (5) and (7) for the relative density estimates was 2.39 schools/1000 km^2 (Table 5). Numerical calculations completed in applying equations (5) and (7) for detection rates of inshore data truncated at 2.13 km are presented in Apppendix 1.

Total Area

Observers on both vessels searched a total of 74,407 km in all areas and detected 741 dolphin schools within 7.40 km perpendicular distance of the trackline and 489 schools within 2.13 km.

The LT density estimate using a 6-term FS model for smeared perpendicular distance distribution data in all areas was 2.95 schools/1000 km^2 with a standard error of 0.253 (Table 5). Detection rates for data truncated at 7.40 and 2.13 km are presented in Table 3. Absolute density estimates calculated using equations (5) and (7) and detection rates for data truncated at 2.13 and 7.4 km were 3.74 and 3.75 schools/1000 km^2. respectively (Table 3). Relative density estimates for ship data in the total area are presented in Table 4. The absolute density estimate using equations (5) and (7) and relative density estimates was 4.04 schools/1000 km^2 (Table 5).

DISCUSSION

Onshore-Offshore Density Gradients

A decreasing onshore-to-offshore dolphin density gradient was illustrated using aerial data in the inshore area and by comparing inshore and offshore density estimates. Although the distributions of sea state and sun glare were confounded with distance from shore within the inshore area, comparisons of detection rates in the two inshore density bands for data stratified by individual Beaufort state or by sun conditions indicated lower rates in the outer band (Figure 16). In addition, offshore density estimates (table 5), corrected for sea state, were only about one-half the inshore estimates (Table 2).

Line Transect Assumptions

Aerial Data

Spatial confounding made it impossible to test the assumption that all trackline schools were detected during aerial surveys. The distribution of perpendicular distances for aerial data in the calibration area differed during calm and rough seas (Figure 23). The calm sea distribution had a spike in the first interval (0-0.27 km) and few sightings in the second interval (0.27-0.65 km). The rough sea distribution had a spike in the second interval and few sightings in the first interval. This disparity may have been caused by errors of observation or by variation associated with small sample sizes.

Neither of these reasons, however, is entirely convincing. For example, it is inconsistent that during rough seas how observers could not detect schools on the trackline but could see them farther away from the pathline, and also that off-track schools were relatively less visible during calm conditions than during rough conditions. Recording errors could have ocurred, but it is not clear why observers would have rounded their estimates in opposite directions during the two sea conditions. The distributions may be due to sampling variability since only 29 schools were detected during calm seas and 27 during rough seas (Table 1). In fact, distributions for all aerial data in the inshore area during calm and rough seas, which had much larger sample sizes, had less pronounced modes (Figure 23). The same general patterns, however, are still present. These patterns were not present for aerial data collected to test sea state differences (Holt 1984)[8].

The above described differences in sighting distance distribution may cause density estimates based upon the calm and rough sea distributions to be biased. If rounding errors occurred then the calm sea density estimate would be positively biased but the rough sea estimate would be negatively biased. If the distribution is true to that encountered during the limited sampling, the FS model underestimated the frequency mode in the first interval of the calm sea sighting distribution (Figure 23) but overestimated the frequency mode in the first interval of the rough sea data. Therefore, calm sea estimates may be negatively biased and rough sea estimaes may be positively biased.

Holt (1984)[8] conducted an aerial experiment in a relatively small area to test sea state and sun effects upon line transect density estimates. The results indicated that sun glare adversely affected estimates of school density and, although sea state estimates were larger for calm sea data than for rough sea data, the differences were not significant. The density estimate was 39% larger during good sun conditions than during poor conditions.

Using these results to adjust the 1977 and 1979 aerial estimates for sun glare effects may not be valid because of differences in the procedures followed in the experiment and the surveys. Viewing conditions aboard the airplanes used for the experiment and for the two aerial surveys differed greatly. The wings on the aircraft used during the experiment were attached on the lower part of the fuselage, whereas wings on the 1977 and 1979 aircraft were attached to the upper part of the craft, thus allowing much better views.

Sun conditions during the surveys and the experiment were not the same. Observers during the surveys were instructed to stop searching if they believed conditions prevented their detecting trackline schools, but observers in the experiment searched during all conditions. In the 1977 survey, searching was occasionally discontinued because of trackline glare, but during the 1979 survey, an additional observer searched the trackline through a rear port in the bottom of the plane when forward sun glare was a problem. The extra observer's effectiveness could not be determined since the adverse conditions usually occurred in the most offshore part of the inshore area, where the school density was low.

Sea conditions differed during the experiment and during the surveys. More rough seas were encountered during the surveys (74%) than in the experiment (62%). Also, more (46% as compared to 15%) of the surveys' total effort occurred at extreme Beaufort 4 and 5 conditions. If conditions during the surveys and the experiment were similar, then the relative rates among the Beaufort states at which dolphins were detected should be similar. This could not be determined for the higher Beaufort states because during the experiment Beaufort 5 conditions existed only 2% of the time. However, during the experiment, Beaufort 4 trackline rates were lower than Beaufort 3 rates, but the surveys' Beaufort 4 and Beaufort 5 trackline rates were slightly larger than Beaufort 3 rates (Figure 24).

Because the amount of effort at the higher Beaufort states differed during the surveys and the experiment, I eliminated Beaufort 5 data and then Beauforts 4 and 5 data from the analyses to allow comparison with the expeimental data (see Appendix 2). Absolute density estimates for the inshore and offshore areas increased as the extreme Beaufort conditions were omitted (Table 6). Because of the spatial distribution of Beaufort 4 and 5 conditions in the inshore area, the larger estimates may be due to elimination of data in the lower density offshore band (Figure 15).

If survey conditions during the surveys and the experiment were comparable, then adjustment factors must be developed for the aerial inshore and calibration data. The aerial data must be adjusted by sea state category since the ship data was corrected by sea state. The adjustments also could be made for data with the extreme Beaufort states omitted.

I used three separate adjustment methods: (1) only data for Beaufort states 1-3 were used so that stratification by sea state conditions was not required and data were stratified only by sun glare conditions; (2) small sample size existed for calibration survey data, and the data were stratified only by sea state categories; and (3) the aerial inshore survey data were stratified by sun glare and sea state categories.

The adjusted density estimate ($\hat{D}_A$) for the first situation is:

$$\hat{D}_A = \frac{(\hat{D}_p)(\hat{P}_p)\hat{D}_g}{\hat{D}'_p} + (\hat{D}_g(1-P)) \qquad (8)$$

where $\hat{D}_p$ = Density estimate in survey area during poor sun conditions,

$\hat{D}_g$ = Density estimate in survey area during good sun conditions,

$\hat{P}_p$ = Proportion of effort in survey area with poor sun conditions,

$\hat{D}'_g$ = Experimental density estimate during good sun conditions determined from Holt (1984)[8],

$\hat{D}'_p$ = Experimental density estimate during poor sun conditions determined from Holt (1984)[8].

An estimate of the sampling variance ($Var(\hat{D}_A)$) using the Taylor approximation method is:

$$Var(\hat{D}_a) = P_p^2\left[\left(\frac{\hat{D}_p}{\hat{D}'_p}\right)^2 var(\hat{D}'_g) + \left(\frac{\hat{D}'_g}{\hat{D}'_p}\right)^2 var(\hat{D}_p) + \left(\frac{\hat{D}_p\hat{D}'_g}{(\hat{D}'_p)^2}\right)^2 var(\hat{D}'_p)\right] + (1-P_p)^2 var(\hat{D}_g) \qquad (9)$$

For the second case, an adjusted density estimate for the ith sea state category (derived in Appendix 3) is:

$$\hat{D}_{Ai} = \frac{\hat{D}_{ci}}{\left[1 - P_{pi} + \frac{\hat{D}'_{pi}}{\hat{D}'_{gi}}(P_{pi})\right]}$$

where $\hat{D}_{ci}$ = density estimate in the survey area during the ith sea state conditions for pooled sun conditions.

Other terms are as defined for equation (8) except for the ith sea state. The combined density estimate ($\hat{D}_u$) pooled for calm (c) and rough (r) sea states is:

$$\hat{D}_u = (P_r)(\hat{D}_{Ar}) + (1-P_r)(\hat{D}_{Ac})$$

where P_r = proportion of rough sea conditions in the study area,

$\hat{D}_{Ar}$ = adjusted density estimate for rough sea conditions in the study area,

$\hat{D}_{Ac}$ = adjusted density estimate for calm sea conditions in the study area.

The variance for $\hat{D}_u$ is:

$$Var(D_u) = (P_r)^2\, var(\hat{D}_{Ar}) + (1-P_r)^2\, var(\hat{D}_{Ac}) + 2(P_r)(1-P_r)\, Cov(\hat{D}_{Ar}, \hat{D}_{Ac})$$

where a correlation coefficient of 0.5 was used.

The third method is a special case of the first, except the data are stratified into calm and rough sea states, and then each sea state category is further stratified into good and poor sun strata. Equation (8) is applied within each sea state category and then equation (9) is used to combine the strata.

Use of an adjustment factor increased the aerial estimates from 20% to 30% depending upon Beaufort states omitted from the analysis (Table 6). Increases inshipboard estimates were also in the same range, depending upon relative index chosen and Beaufort states omitted. The maximum increase for aerial inshore and offshore estimates between unadjusted data and data adjusted for sea state (Beauforts 4 and 5 omitted) and sun glare was 76% and 64%, respectively.

Comparisons of the observer teams' estimates failed to indicate observers of either team missed dolphin schools on the trackline but both teams may have been equally affected by searching conditions. This was consistent with results of the aerial experiment (Holt 1984)[8] where comparisons of observer teams' performance also indicated no significant differences.

Ship Data

Sea state conditions may have adversely affected density estimates using ship data. The larger relative density indices calculated for calm sea condiditons may have been caused by (1) actual density differences surveyed during calm and rough sea states, (2) observers missing trackline schools during rough sea conditions, or (3) observers detecting schools at greater radial distances during calm conditions (mean radial distance was 4.16 kn) than during rough conditions (mean radial distance was 3.55 km). Estimation of sighting angles and distances for schools at greater distances from the ship may have been less accurate and may have increased the probability of a school's being erroneously recorded near or on the indices, either with detection rate or relative density data, attempted to adjust for these effects by using aerial and ship data stratified by sea state categories.

Although sun glare was not shown to affect the shipboard density estimates, Cologne and Holt (1984)[6] indicate that shipboard observers tend to avoid searching areas with sun glare. However, because of the relatively slow speed of the ship and the dolpins, all areas may be scrutinized in the absence of glare.

The perpendicular distance distributions for the 1982 and 1983 TVE teams were greatly different but their distributions of searching angles were similar (Cologne and Holt 1984)[6]. Absolute density estimates calculated with detection rate data truncated at 2.13 km were the only estimates not affected by the TVE team's distributions. Within 2.13 km of the track, detection rates for TVE teams in both years were similar to the RVE team's estimates.

Data Treatment Effects

I calculated absolute density estimates for ship data using relative indices (equations 5 and 7) that were stratified by sea state categories where data were available. The 1977 ship data could not be stratified by sea state but I calculated unstratified estimates for each ship's data (Equation 5) and combined them (equation 7) with the stratified estimates for all other years' data to form the absolute density estimate (Table 5). The effect of using the unstratified 1977 data depends upon the relative amount of calm and rough seas encountered during the surveys in the offshore and calibration areas. If rough seas were encountered substantially more often in the offshore area, then the absolute density estimate may be negatively biased. The maximum bias possible can be determined by assuming that all offshore effort was conducted during rough sea conditions. For this assumption, offshore absolute density estimates, using detection rate data truncated at 2.13 km from the trackline, was 2.27 schools/1000 km^2 with a standard error of 0.560 . This is similar to the unstratified estimate of 2.16 schools/1000 km^2 (Table 5). Therefore, the actual bias possible was small.

The valid use of detection rates, relative densities, or LT densities to determine absolute density estimates for ship data required increasingly more stringent assumptions. Use of detection rates as relative indices required that (1) the aerial absolute density estimates in the calibration area were accurate and (2) the factors affecting the rate of detecting schools were consistent between the calibration area and the area for which density was estimated. The data were stratified by sea state categories to alleviate the requirement that sea conditions between areas be equivalent.

I investigated the differential influence on factor (2) of birds as sighting cues in the calibration and offshore areas. If dolphins accompanied by birds were more detectable at greater perpendicular distances from the ships than were unaccompanied schools, and if the birds occur more frequently in the calibration area, as suspected, then offshore absolute density estimates (using equation 5) would be negatively biased. In fact, density estimates were slightly smaller using data truncated at 7.4 km perpendicular distance than for data truncated at 2.13 km (Table 5).

I examined the association of the sighting cues used to detect dolphins (animal splashes, birds, and the animals themselves) and the perpendicular distance at which schools were detected by analysis of variance and Tukey's tests. For data truncated at 7.4 km perpendicular distance, bird-associated schools were detected at significantly greater distances (2.61 km mean perpendicular distance) than were schools detected by splashes (1.91 km mean perpendicular distance) ($P>0.01$). Schools located by sighting the animals themselves were detected significantly closer (1.52 km mean perpendicular distance). For schools detected within 2.13 km of the trackline, the mean distance at which bird-associated schools (0.89 km mean distance) were detected was not significantly different from distances at which schools were detected by splashes (0.98 km mean distance) or by the presence of the animals (0.76 km mean distance). The mean distances at which schools were detected by splashes and at which the animal was the cue differed significantly.

Use of ship relative density indices further assumed that data used to calculate the perpendicular distance to the dolphin schools, especially those near the trackline, was consistent between the calibration area and the area for which density was estimated. The LT model must also be applied consistently to data in both areas. In addition, the method requires a minimum number of sightings in each data stratum: at least 30 schools are desired (Burnham et al. 1980). The number of schools in some strata were less than minimal so unstratified relative density estimates were calculated.

Finally, direct use of line transect methods for ship data (LT estimator) required that all line transect assumptions be met or at least accommodated in some manner. For example, the perpendicular distance distributions were smeared to help alleviate data recording errors. Selection of appropriate data treatment factors such as truncation values may be critical, especially for data with recognized inaccuracies. The method may avoid use of small sample sizes, since the data does not have to be stratified for various detection factors.

If the assumptions of each method are met, then absolute density estimates for the three methods (detection rates, relative densities, and LT densities) applied to the same data set should be comparable. Estimates using these methods for offshore data differed only slightly (Table 5).

The variances associated with the three estimates, however, were greatly different. The coefficient of variation for the offshore estimates using the LT density method was much smaller than those of the other two methods. Because of its similarity to the other offshore estimates and because of its smaller coefficient of variation, the LT density method was chosen to estimate offshore absolute density.

The estimate of dolphin density for the inshore area using the LT density estimate (Table 5) was larger than the corresponding aerial estimate (Table 2). The ship surveys were not intended to survey the entire inshore area but rather the calibration and offshore areas. Therefore, ships spent 61% of their inshore effort in the high density calibration area although it represented only 44% of the inshore area (Table 7). Furthermore, ships spent little effort in the southern inshore area during the 1979, 1980, or 1982 surveys (Figure 25). The aerial surveys spent only 41% of their effort in the calibration area and conducted a systematic survey of the entire area. Therefore the aerial density estimate was more representative of the inshore dolphin density.

Estimates for the total area using ship data were also biased because of oversampling the inshore area. Although the inshore area represented only 31% of the total area (Table 7), 38% of the ship's effort was in the inshore area. The same bias caused by oversampling the calibration area within the inshore area would further bias the overall estimate.

To avoid the inshore sampling bias, I calculated an estimate of the total area by pooling the aerial estimate (Table 2) for the inshore area with the offshore LT ship estimate (Table 5) weighted by the respective size of the two areas (Table 7). This yielded a density estimate for the total area of 2.71 schools/1000 km^2.

Comparisons of Annual Density Estimates

Density estimates for each year's data varied greatly (Figure 26). Absolute density estimates, using equations (5) and (7) and detection rates for 2.13 km truncated data were lowest for 1977 data and highest for the 1980 inshore data. Because coverage in some areas was sparse in some years (Figure 25), the location of the survey within areas may have affected the density estimates. In addition, the relative amount of effort in each area may have affected overall estimates. For example, the 1977 surveys spent only 14% of their effort in the inshore area (Table 7) and none of that was in the high density calibration area. The 1977 offshore effort included the most westward boundary areas. The 1979 surveys, however, spent 64% of their effort in the inshore area, although the area represented only 31% of the total. In addition, 86% of the inshore effort was in the calibration area, which represents only 44% of the inshore area.

Finally, seasonal effects may be substantial. The 1980 surveys were concentrated along the 10° N latitudinal during winter (January-March), whereas the 1982 survey covered the same areas during summer (May-August). The density estimate for the inshore area was much higher during the winter than during the summer, but offshore estimates were approximately equal (Figure 26).

Comparisons with Previous Density Estimates

The ETP dolphin stocks have been estimated previously (SWFC 1976[9], Holt and Powers 1982). The present estimates were calculated with methods similar to the Holt and Powers assessment. Therefore, differences noted by them between the 1979 assessment and the 1976 assessment are also applicable to comparisons of the 1976 assessment and this study. The present estimates differ from the 1979 assessment in that they include:

1. schools where either the mean observer's "best" or "lowest" estimate of school size was greater than 14 animals; the 1979 assessment included only schools with mean "best" estimates

2. all aerial calibration data ; the 1979 assessment did not include a small amount where there was no corresponding ship data

3. use of the 1977 aerial data in the inshore density estimate

4. correction factors relating aerial absolute density estimates to ship relative indices stratified by sea state categories

5. ship data collected in 1977, 1979, 1980, 1982, and 1983; the 1979 assessment included only 1979 ship data

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[9]SWFC (Southwest Fisheries Center, Nat'l Mar. Fish. Serv., NOAA, La Jolla, Ca 92038). 1976. Report of the workshop on stock assessment of porpoises involved in the eastern tropical Pacific yellowfin tuna fishery. Southwest Fish. Cent. Adm. Rep. No. LJ-76-29, La Jolla, CA 60 pp.

6. investigation of aerial and ship data for effects of sun, sea state, and observer performance

7. application of line transect methods to ship data to calculate absolute density estimates.

Unadjusted density estimates, utilizing the complete data set, calculated in this study were very similar to those presented in the 1979 assessment (Holt and Powers 1982). The aerial inshore estimate was based upon essentially the same data. Including the 1977 aerial data had little effect on the mean estimate, but variability associated with the estimate decreased slightly. The unadjusted offshore density estimates calculated using several options ranged slightly above the 1979 offshore estimate.

The present offshore estimate, however, is based upon much more extensive geographic coverage than was used in 1979; data has been stratified by sea state effects; and analyses have been based upon LT methods. These methods substantially reduced the variability associated with the estimates.

CONCLUSIONS

LT methods were used on 1977 and 1979 aerial survey data to estimate dolphin density in the inshore area at 4.18 schools/1000 km^2. LT methods applied to ship data yielded an estimate of offshore dolphin density of 2.04 schools/1000 km^2. By pooling aerial inshore and ship offshore data weighted by the respective size of the two areas, the total dolphin density was estimated at 2.71 schools/1000 km^2.

Several options for adjusting the data for sea state and sun conditions increased the inshore aerial density estimate a maximum of 76% and the offshore ship density estimate by 64%. However, sea state adjustments were completed by omitting rough sea state data located mainly in the lower density areas and sun glare adjustments were completed by using data from an experimental aerial survey which encountered survey conditions different from those found during the aerial surveys.

The unadjusted inshore and offshore estimates are very similar to a 1979 assessment.

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Table 1. Distribution of perpendicular distance for schools detected during the aerial and ship surveys. Data are stratified by calm (Csea) and rough (Rsea) sea, good (Gsun) and poor (Psun) sun conditions, and vessel (DSJ = Jordan and TC = Cromwell).

Perpendicular Distance (km)

AERIAL DATA

Variable	0.0 - 0.09	0.09 - 0.28	0.28 - 0.46	0.46 - 0.65	0.65 - 0.83	0.83 - 1.02	1.02 - 1.20	1.20 - 1.39	1.39 - 1.57	1.57 - 1.76	1.76 - 1.94	Total Sightings
1979 Calibration Area												
All Data	13	17	10	2	4	3	3	1	1	1	1	56
Csea	9	3	6	2	2	1	3	1	1	1	0	29
Rsea	4	14	4	0	2	2	0	0	0	0	1	27
Gsun	9	9	5	0	1	1	1	0	0	0	1	27
Psun	4	8	5	2	3	2	2	1	1	1	0	29
Csea-Gsun	7	1	3	0	1	1	1	0	0	0	0	14
Csea-Psun	2	2	3	2	1	0	2	1	1	1	0	15
Rsea-Gsun	2	8	2	0	0	0	0	0	0	0	1	13
Rsea-Psun	2	6	2	0	2	2	0	0	0	0	0	14
1979 Inshore Area												
All Data	28	40	32	17	11	6	4	4	5	3	2	152
Csea	17	12	17	8	3	3	3	2	3	2	0	70
Rsea	11	28	15	9	8	3	1	2	2	1	2	82
Gsun	15	22	13	7	3	3	1	3	3	2	2	74
Psun	13	18	19	10	8	3	3	1	2	1	0	78
Csea-Gsun	9	5	7	2	1	2	1	1	1	1	0	30
Csea-Psun	8	7	10	6	2	1	2	1	2	1	0	40
Rsea-Gsun	6	17	6	5	2	1	0	2	2	1	2	44
Rsea-Psun	5	11	9	4	6	2	1	0	0	0	0	38

SHIP DATA

Data Source & Area	Variable	0.0 - 0.27	0.27 - 0.65	0.65 - 1.02	1.02 - 1.39	1.39 - 1.76	1.76 - 2.31	2.31 - 2.78	2.78 - 3.24	3.24 - 3.70	Total Sightings
77 DSJ Offshore	All Data	19	8	8	10	8	8	12	3	6	82
77 TC Offshore	All Data	3	3	2	2	1	0	0	0	4	15
77 DSJ Inshore	All Data	3	6	4	8	6	5	5	2	1	40
79 DSJ Calibration	All Data	26	10	20	7	6	11	14	5	3	102
79 DSJ Calibration	Csea	18	8	17	6	3	7	11	5	3	78
79 DSJ Calibration	Rsea	8	2	3	1	3	4	3	0	0	24
79 TC Calibration	All Data	11	2	7	8	5	8	2	4	2	49
79 TC Calibration	Csea	5	2	6	3	1	4	0	3	2	26
79 TC Calibration	Rsea	6	0	1	5	4	4	2	1	0	23
79-83 DSJ Offshore	All Data	37	21	11	9	11	14	13	4	7	127
79-83 DSJ Offshore	Csea	17	6	5	5	3	7	5	2	6	56
79-83 DSJ Offshore	Rsea	20	15	6	4	8	7	8	2	1	71
79-80 TC Offshore	All Data	7	4	4	1	1	3	0	1	0	21
79-80 TC Offshore	Csea	0	1	0	0	0	0	0	1	0	2
79-80 TC Offshore	Rsea	7	3	4	1	1	3	0	0	0	19
79-83 DSJ Inshore	All Data	59	31	35	23	24	30	28	17	8	255
79-83 DSJ Inshore	Csea	31	22	20	9	12	14	18	9	4	139
79-83 DSJ Inshore	Rsea	28	9	15	14	12	16	10	8	4	116
79-80 TC Inshore	All Data	18	11	15	13	6	10	3	7	4	87
79-80 TC Inshore	Csea	9	8	9	5	1	6	0	5	2	45
89-80 TC Inshore	Rsea	9	3	6	8	5	4	3	2	2	42

Table 2. Estimates of school density for 1979 aerial calibration and 1977 plus 1979 aerial inshore data. Data are stratified by calm (Csea) and rough (Rsea) sea and good (Gsun) and poor (Psun) sun conditions.

Variable	Distance Searched (km)	Number Terms in model	Number Schools Detected (n)	S.E.(n)	$\hat{f}$ (0)	S.E.$\hat{f}$ (0)	Density ($\hat{D}$) (Schools/ 1000 (km^2))	Var ($\hat{D}$)	S.E.($\hat{D}$)	C.V. ($\hat{D}$)	Number Flights
79 PBY Calibration Area											
All Data	10869	5	56	11.51	2.38	0.270	6.13	2.072	1.439	0.235	10
Csea	2455	9	29	4.56	2.30	0.749	13.59	24.135	4.913	0.362	10
Rsea	8414	4	27	10.44	2.44	0.274	3.91	2.485	1.576	0.403	10
Gsun	4084	6	27	8.07	3.34	0.318	11.04	11.995	3.463	0.314	10
Psun	6784	3	29	6.43	1.44	0.260	3.08	0.775	0.880	0.286	10
77+79 PBY Inshore Area											
All Data	34006	9	152	19.66	1.87	0.323	4.18	0.813	0.902	0.216	26
Csea	8920	9	70	9.20	2.16	0.483	8.48	4.832	2.198	0.259	23
Rsea	25086	3	82	17.06	1.66	0.143	2.71	0.373	0.611	0.255	26
Gsun	11994	6	74	12.92	2.13	0.315	6.57	2.261	1.504	0.229	23
Psun	22012	3	78	11.77	1.62	0.147	2.87	0.255	0.505	0.176	25
Csea-Gsun	3026	9	30	9.00	2.55	0.744	12.64	27.980	5.290	0.418	17
Csea-Psun	5894	9	40	5.98	1.84	0.623	6.24	5.341	2.311	0.370	21
Rsea-Gsun	8967	3	44	11.49	1.75	0.176	4.29	1.444	1.202	0.280	22
Rsea-Psun	16118	2	38	9.81	1.51	0.004	1.78	0.211	0.460	0.258	25

Table 3. Detection rates for all ship data and stratified by year, vessel (DSJ = Jordan and TC = Cromwell), and sea state categories for truncation distances of 2.13 and 7.40 km in the offshore, inshore, calibration and all areas.

				7.4 km Perpendicular Distance				2.13 km Perpendicular Distance				
Data Source	Variable	Distance Searched (km)	Percent (km) Searched	Number Schools Detected	Percent All Schools Detected	Detection Rate (Schools/ 1000 km)	S.E. (Detection Rate)	Number Schools Detected	Percent Schools Detected	Detection Rate (Schools/ 1000 km)	S.C. (Detection Rate)	Number Days Searched
Calibration Area												
79-83 Both	All Data	16843	100.0	301	100.0	17.87	1.62	190	100.0	11.28	1.32	106
79-83 Both	Csea	5681	33.7	161	53.5	28.34	3.28	98	51.6	17.25	2.66	60
79-83 Both	Rsea	11163	66.3	140	46.5	12.54	1.34	92	48.4	8.24	1.08	86
79-83 DSJ	All Data	10968	100.0	216	100.0	19.69	2.33	140	100.0	12.76	1.92	66
79-83 DSJ	Csea	4149	37.8	122	56.5	29.41	4.46	77	55.0	18.56	3.67	38
79-83 DSJ	Rsea	6819	62.2	94	43.5	13.79	1.82	63	45.0	9.24	1.40	52
79-83 TC	All Data	5876	100.0	85	100.0	14.47	1.71	50	100.0	8.51	1.27	40
79-83 TC	Csea	1532	26.1	39	45.9	25.46	4.11	21	42.0	13.71	2.89	22
79-83 TC	Rsea	4344	73.9	46	54.1	10.59	1.89	29	58.0	6.68	1.69	34
79 Both	All Data	9776	100.0	185	100.0	18.92	2.17	118	100.0	12.07	1.57	59
79 Both	Csea	3901	39.9	127	68.6	32.56	3.47	78	66.1	20.00	2.51	39
79 Both	Rsea	5875	60.1	58	31.4	9.87	1.57	40	33.9	6.81	1.41	44
79 DSJ	All Data	5286	100.0	121	100.0	22.89	3.74	79	100.0	14.95	2.68	28
79 DSJ	Csea	2583	48.9	94	77.7	36.39	4.85	58	73.4	22.45	3.63	20
79 DSJ	Rsea	2703	51.1	27	22.3	9.99	2.22	21	26.6	7.77	2.01	18
79 TC	All Data	4490	100.0	64	100.0	14.25	1.93	39	100.0	8.69	1.43	31
79 TC	Csea	1318	29.4	33	51.6	25.04	4.65	20	51.3	15.18	3.21	19
79 TC	Rsea	3172	70.6	31	48.4	9.77	2.24	19	48.7	5.99	1.98	26
80 Both	All Data	2930	100.0	57	100.0	19.45	4.95	40	100.0	13.65	4.79	21
80 Both	Csea	774	26.4	18	31.6	23.26	13.01	11	27.5	14.21	13.00	10
80 Both	Rsea	2156	73.6	39	68.4	18.09	3.33	29	72.5	13.45	2.89	17
80 DSJ	All Data	1544	100.0	36	100.0	23.31	8.46	29	100.0	18.78	8.29	12
80 DSJ	Csea	560	36.3	12	33.3	21.44	18.44	10	34.5	17.86	18.47	7
80 DSJ	Rsea	984	63.7	24	66.7	24.38	5.08	19	65.5	19.30	4.10	9
80 TC	All Data	1386	100.0	21	100.0	15.16	3.89	11	100.0	7.94	2.88	9
80 TC	Csea	214	15.4	6	28.6	28.03	8.27	1	9.1	4.67	3.19	3
80 TC	Rsea	1172	84.6	15	71.4	12.80	3.62	10	90.9	8.54	3.37	8
82 DSJ	All Data	2617	100.0	32	100.0	12.23	2.61	18	100.0	6.88	2.04	16
82 DSJ	Csea	606	23.1	4	12.5	6.61	3.13	2	11.1	3.30	1.68	5
82 DSJ	Rsea	2012	76.9	28	87.5	13.92	3.68	16	88.9	7.95	2.36	15
83 DSJ	All Data	1521	100.0	27	100.0	17.76	3.49	14	100.0	9.21	2.52	10
82 DSJ	Csea	401	26.4	12	44.4	29.96	11.28	7	50.0	17.48	6.64	6
83 DSJ	Rsea	1120	73.6	15	55.6	13.39	4.40	7	50.0	6.25	2.99	10

Table 3 (continued)

				7.4 km Perpendicular Distance				2.13 km Perpendicular Distance				
Data Source	Variable	Distance Searched (km)	Percent km Searched	Number Schools Detected	Percent All Schools Detected	Detection Rate (Schools/ 1000 km)	S.E. Detection Rate	Number of Schools Detected	Percent Schools Detected	Detection Rate (Schools/ 1000 km)	S.E. (Detection Rate)	Number of Days Searched
Inshore Area												
77-83 Both	All Data	27840	100.0	460	100.0	16.52	1.11	297	100.0	10.67	0.82	173
79-83 Both	All Data	24112	100.0	414	100.0	17.17	1.17	267	100.0	11.07	0.88	151
79-83 Both	Csea	8502	35.3	228	55.1	26.82	2.12	144	53.9	16.94	1.52	89
79-83 Both	Rsea	15609	64.7	186	44.9	11.92	1.16	123	46.1	7.88	0.92	124
79-83 DSJ	All Data	16623	100.0	304	100.0	18.29	1.57	196	100.0	11.79	1.17	101
79-83 DSJ	Csea	6187	37.2	170	55.9	27.48	2.71	107	54.6	17.29	1.90	59
79-83 DSJ	Rsea	10436	62.8	134	44.1	12.84	1.52	89	45.4	8.53	1.17	82
79-83 TC	All Data	7488	100.0	110	100.0	14.69	1.52	71	100.0	9.48	1.18	50
79-83 TC	Csea	2315	30.9	58	52.7	25.05	3.24	37	52.1	15.98	2.56	30
79-83 TC	Rsea	5173	69.1	52	47.3	10.05	1.69	34	47.9	6.57	1.49	42
77 Both	All Data	3728	100.0	46	100.0	12.34	3.19	30	100.0	8.05	2.12	22
79 Both	All Data	11337	100.0	205	100.0	18.08	1.98	133	100.0	11.73	1.46	68
79 Both	Csea	4674	41.2	142	69.3	30.38	3.15	90	67.7	19.25	2.30	45
79 Both	Rsea	6663	58.8	63	30.7	9.46	1.54	43	32.3	6.45	1.25	51
79 DSJ	All Data	6526	100.0	138	100.0	21.15	3.18	92	100.0	14.10	2.35	35
79 DSJ	Csea	3217	49.3	106	76.8	32.95	4.32	68	73.9	21.14	3.23	25
79 DSJ	Rsea	3309	50.7	32	23.2	9.67	2.26	24	26.1	7.25	1.66	23
80 Both	All Data	6447	100.0	118	100.0	18.30	1.74	85	100.0	13.19	1.45	42
80 Both	Csea	2303	35.7	53	44.9	23.01	2.56	39	45.9	16.93	2.39	25
80 Both	Rsea	4143	64.3	65	55.1	15.69	2.30	46	54.1	11.10	1.96	35
80 DSJ	All Data	3770	100.0	75	100.0	19.90	2.39	55	100.0	14.59	1.98	25
80 DSJ	Csea	1446	38.4	31	41.3	21.44	3.01	24	43.6	16.60	2.51	15
80 DSJ	Rsea	2324	61.6	44	58.7	18.93	3.29	31	56.4	13.34	2.81	21
82 DSJ	All Data	3378	100.0	40	100.0	11.84	2.17	21	100.0	6.22	1.62	22
82 DSJ	Csea	846	25.0	7	17.5	8.27	2.95	2	9.5	2.36	1.13	9
82 DSJ	Rsea	2532	75.0	33	82.5	13.03	3.06	19	90.5	7.50	1.94	19
83 DSJ	All Data	2950	100.0	51	100.0	17.29	3.82	28	100.0	9.49	2.51	19
83 DSJ	Csea	678	23.0	26	51.0	38.34	8.26	13	46.4	19.17	4.22	10
83 DSJ	Rsea	2272	77.0	25	49.0	11.01	3.54	15	53.6	6.60	2.88	19

Table 3 (continued)

Data Source	Variable	7.4 km Perpendicular Distance: Distance Searched (km)	Percent km Searched	Number Schools Detected	Percent All Schools Detected	Detection Rate (Schools/ 1000 km)	S.E. (Detection Rate)	2.1 km Perpendicular Distance: Number Schools Detected	Percent Schools Detected	Detection Rate (Schools/ 1000 km)	S.E. Detection Rate	Number Days Searched
Offshore Area												
77-83 Both	All Data	46567	100.0	281	100.0	6.03	0.66	192	100.0	4.12	0.50	251
79-83 Both	All Data	24144	100.0	172	100.0	7.12	1.04	120	100.0	4.97	0.77	143
79-83 Both	Csea	4129	17.1	68	39.5	16.47	3.17	44	36.7	10.66	2.30	58
79-83 Both	Rsea	20015	82.9	104	60.5	5.20	0.67	76	63.3	3.80	0.56	134
79-83 DSJ	All Data	16583	100.0	150	100.0	9.05	1.43	100	100.0	6.03	1.05	101
79-83 DSJ	Csea	3827	23.1	66	44.0	17.25	3.47	43	43.0	11.24	2.53	51
79-83 DSJ	Rsea	12756	76.9	84	56.0	6.58	0.91	57	57.0	4.47	0.77	92
79-83 TC	All Data	7561	100.0	22	100.0	2.91	0.70	20	100.0	2.65	0.65	42
79-83 TC	Csea	303	4.0	2	9.1	6.61	4.34	1	5.0	3.30	2.17	7
79-83 TC	Rsea	7258	96.0	20	90.9	2.76	0.72	19	95.0	2.62	0.69	42
77 Both	All Data	22423	100.0	109	100.0	4.86	0.72	72	100.0	3.21	0.59	108
77 DSJ	All Data	15433	100.0	94	100.0	6.09	0.97	61	100.0	3.95	0.79	76
77 TC	All Data	6991	100.0	15	100.0	2.15	0.62	11	100.0	1.57	0.56	32
79 Both	All Data	6386	100.0	60	100.0	9.40	3.54	45	100.0	7.05	2.54	35
79 Both	Csea	1872	29.3	43	71.7	22.97	7.33	31	68.9	16.56	5.02	20
79 Both	Rsea	4514	70.7	17	28.3	3.77	1.70	14	31.1	3.10	1.65	31
79 DSJ	All Data	3464	100.0	51	100.0	14.72	6.10	37	100.0	10.68	4.35	20
79 DSJ	Csea	1610	46.5	41	80.4	25.46	8.96	30	81.1	18.63	6.10	15
79 DSJ	Rsea	1854	53.5	10	19.6	5.39	3.39	7	18.9	3.78	3.30	16
80 Both	All Data	8456	100.0	43	100.0	5.09	0.97	34	100.0	4.02	0.88	51
80 Both	Csea	485	5.7	5	11.6	10.30	4.95	4	11.8	8.24	4.94	8
80 Both	Rsea	7970	94.3	38	88.4	4.77	0.95	30	88.2	3.76	0.85	49
80 DSJ	All Data	3817	100.0	30	100.0	7.86	1.71	22	100.0	5.76	1.63	24
80 DSJ	Csea	444	11.6	5	16.7	11.25	5.95	4	18.2	9.00	6.00	6
80 DSJ	Rsea	3372	88.4	25	83.3	7.41	1.73	18	81.8	5.34	1.62	22
82 DSJ	All Data	6066	100.0	53	100.0	8.74	1.36	28	100.0	4.62	0.96	36
82 DSJ	Csea	1562	25.8	18	34.0	11.53	2.51	7	25.0	4.48	1.93	23
82 DSJ	Rsea	4504	74.2	35	66.0	7.77	1.45	21	75.0	4.66	0.93	33
83 DSJ	All Data	3236	100.0	16	100.0	4.94	1.25	13	100.0	4.02	0.94	21
83 DSJ	Csea	210	6.5	2	12.5	9.51	3.15	2	15.4	9.51	3.15	7
83 DSJ	Rsea	3026	93.5	14	87.5	4.63	1.30	11	84.6	3.64	1.02	21

Table 3 (continued)

Data Source	Variable	Distance Searched (km)	Percent km Searched	7.4 km Perpendicular Distance: Number Schools Detected	Percent All Schools Detected	Detection Rate (Schools/ 1000 km	S.E. (Detection Rate)	2.1 km Perpendicular Distance: Number Schools Detected	Percent Schools Detected	Detection Rate (Schools/ 1000 km	S.E. (Detection Rate)	Number Days Searched
All Areas												
77-83 Both	All Data	74407	100.0	741	100.0	9.96	0.64	489	100.0	6.57	0.47	417
79-83 Both	All Data	48256	100.0	586	100.0	12.14	0.84	387	100.0	8.02	0.61	290
79-83 Both	Csea	12632	26.2	296	50.5	23.43	1.81	188	48.6	14.88	1.29	146
79-83 Both	Rsea	35624	73.8	290	49.5	8.14	0.67	199	51.4	5.59	0.54	256
79-83 DSJ	All Data	33206	100.0	454	100.0	13.67	1.11	296	100.0	8.91	0.82	199
79-83 DSJ	Csea	10014	30.2	236	52.0	23.57	2.19	150	50.7	14.98	1.54	109
79-83 DSJ	Rsea	23192	69.8	218	48.0	9.40	0.89	146	49.3	6.30	0.70	173
79-83 TC	All Data	15049	100.0	132	100.0	8.77	1.05	91	100.0	6.05	0.77	91
79-83 TC	Csea	2618	17.4	60	45.5	22.92	2.97	38	41.8	14.52	2.29	37
79-83 TC	Rsea	12431	82.6	72	54.5	5.79	0.94	53	58.2	4.26	0.80	83
77 Both	All Data	26151	100.0	155	100.0	5.93	0.81	102	100.0	3.90	0.61	127
77 DSJ	All Data	19161	100.0	140	100.0	7.31	1.04	91	100.0	4.75	0.78	95
77 TC	All Data	6991	100.0	15	100.0	2.15	0.62	11	100.0	1.57	0.56	32
79 Both	All Data	17723	100.0	265	100.0	14.95	1.82	178	100.0	10.04	1.31	103
79 Both	Csea	6546	36.9	185	69.8	28.26	3.10	121	68.0	18.48	2.18	65
79 Both	Rsea	11177	63.1	80	30.2	7.16	1.18	57	32.0	5.10	1.01	82
79 DSJ	All Data	9990	100.0	189	100.0	18.92	2.98	129	100.0	12.91	2.15	55
79 DSJ	Csea	4827	48.3	147	77.8	30.45	4.19	98	76.0	20.30	2.96	40
79 DSJ	Rsea	5163	51.7	42	22.2	8.14	1.91	31	24.0	6.00	1.63	39
79 TC	All Data	7733	100.0	76	100.0	9.83	1.53	49	100.0	6.34	1.08	48
79 TC	Csea	1719	22.2	38	50.0	22.11	3.91	23	46.9	13.38	2.63	25
79 TC	Rsea	6014	77.8	38	50.0	6.32	1.46	26	53.1	4.32	1.25	43
80 Both	All Data	14902	100.0	161	100.0	10.80	1.16	119	100.0	7.99	0.94	91
80 Both	Csea	2789	18.7	58	36.0	20.80	2.37	43	36.1	15.42	2.17	32
80 Both	Rsea	12113	81.3	103	64.0	8.50	1.18	76	63.9	6.27	0.98	83
80 DSJ	All Data	7586	100.0	105	100.0	13.84	1.71	77	100.0	10.15	1.43	48
80 DSJ	Csea	1890	24.9	36	34.3	19.05	2.76	28	36.4	14.82	2.38	20
80 DSJ	Rsea	5696	75.1	69	65.7	12.11	1.94	49	63.6	8.60	1.64	43
80 TC	All Data	7316	100.0	56	100.0	7.65	1.42	42	100.0	5.74	1.11	43
80 TC	Csea	899	12.3	22	39.3	24.47	4.44	15	35.7	16.69	4.51	12
80 TC	Rsea	6417	87.7	34	60.7	5.30	1.19	27	64.3	4.21	1.01	40
82 DSJ	All Data	9444	100.0	93	100.0	9.85	1.18	49	100.0	5.19	0.86	57
82 DSJ	Csea	2408	25.5	25	26.9	10.38	1.94	9	18.4	3.74	1.36	32
82 DSJ	Rsea	7036	74.5	68	73.1	9.66	1.47	40	81.6	5.68	0.93	52
83 DSJ	All Data	6186	100.0	67	100.0	10.83	2.17	41	100.0	6.63	1.37	39
83 DSJ	Csea	889	14.4	28	41.8	31.51	6.29	15	36.6	16.88	3.10	17
83 DSJ	Rsea	5297	85.6	39	58.2	7.36	1.82	26	63.4	4.91	1.44	39

Table 4. Relative density estimates for all ship data and stratified by year, vessel (DSJ = Jordan and TC = Cromwell), and calm (Csea) and rough (Rsea) sea conditions.

Data Source	Variable	Number Terms in model	Number Schools Detected (n)	S.E.(n)	$\hat{f}(0)$	S.E.$\hat{f}(0)$	Density ($\hat{D}$) (Schools/1000 km^2)	Var ($\hat{D}$)	S.E. ($\hat{D}$)	C.V. ($\hat{D}$)
Calibration Area										
79 Both	All Data	7	154	15.33	0.70	0.125	5.51	1.271	1.127	0.204
79 DSJ	All Data	7	104	14.14	0.74	0.155	7.28	3.305	1.818	0.250
79 DSJ	Csea	5	79	9.38	0.58	0.129	8.87	5.001	2.236	0.252
79 DSJ	Rsea	7	22	5.44	1.05	0.350	4.27	3.145	1.773	0.415
79 TC	All Data	7	49	6.44	0.67	0.217	3.66	1.633	1.278	0.350
79 TC	Csea	1	26	4.23	0.41	0.068	4.04	0.883	0.940	0.232
79 TC	Rsea	7	24	6.28	0.75	0.314	2.84	1.962	1.401	0.494
Offshore Area										
79-83 DSJ	Csea	6	54	9.66	0.78	0.185	5.50	2.673	1.635	0.297
79-83 DSJ	Rsea	5	70	9.78	0.86	0.143	2.36	0.263	0.513	0.217
79-83 TC	All Data	7	22	4.90	1.04	0.366	1.51	0.397	0.630	0.416
77 Both	All Data	6	95	13.15	0.68	0.135	1.44	0.121	0.349	0.242
77 DSJ	All Data	6	81	12.26	0.69	0.145	1.81	0.220	0.469	0.259
79 Both	All Data	5	54	16.20	0.80	0.167	3.38	1.528	1.236	0.365
80 Both	All Data	6	40	7.47	1.06	0.222	2.51	0.495	0.703	0.281
82 DSJ	All Data	7	38	5.83	0.48	0.220	1.50	0.528	0.726	0.483
83 DSJ	All Data	7	12	3.05	1.83	0.500	3.39	1.603	1.266	0.373
Inshore Area										
79-83 DSJ	Csea	6	140	11.73	0.67	0.112	7.58	2.009	1.417	0.187
79-83 DSJ	Rsea	7	114	12.18	0.80	0.149	4.37	0.880	0.938	0.215
79-83 TC	Csea	5	45	5.94	0.66	0.176	6.41	3.643	1.909	0.298
79-83 TC	Rsea	7	40	7.70	0.80	0.253	3.09	1.311	1.145	0.370
77 Both	All Data	2	40	7.89	0.35	0.093	1.88	0.386	0.621	0.331
79 Both	All Data	6	171	16.55	0.66	0.100	4.98	0.801	0.895	0.180
79 Both	Csea	6	118	10.77	0.65	0.122	8.20	2.932	1.712	0.209
79 Both	Rsea	7	51	8.34	0.82	0.220	3.14	0.972	0.986	0.314
80 Both	All Data	7	102	9.35	0.83	0.161	6.57	1.984	1.409	0.215
82 DSJ	All Data	1	32	5.49	0.38	0.064	1.80	0.187	0.433	0.240
83 DSJ	All Data	6	36	7.41	0.81	0.225	4.94	2.919	1.709	0.346
Total Area										
79-83 DSJ	Csea	6	196	15.45	0.69	0.095	6.75	1.148	1.071	0.159
79-83 DSJ	Rsea	7	187	16.12	0.84	0.118	3.39	0.312	0.558	0.165
79-83 TC	Csea	5	47	5.99	0.60	0.171	5.39	2.827	1.681	0.312
79-83 TC	Rsea	7	62	9.92	0.93	0.210	2.32	0.412	0.642	0.277
77 Both	All Data	5	134	15.85	0.53	0.096	1.36	0.086	0.294	0.216
77 DSJ	All Data	6	122	14.91	0.56	0.114	1.78	0.179	0.423	0.237
77 TC	All Data	2	13	3.90	0.83	0.034	0.77	0.055	0.234	0.303
79 Both	All Data	7	224	23.23	0.74	0.106	4.68	0.684	0.827	0.177
79 Both	Csea	5	157	14.30	0.65	0.094	7.80	1.775	1.332	0.171
79 Both	Rsea	7	68	11.26	0.87	0.196	2.65	0.548	0.740	0.280
80 Both	All Data	6	141	13.95	0.85	0.116	4.02	0.459	0.678	0.169
80 Both	Csea	5	48	6.05	0.76	0.173	6.54	2.896	1.702	0.260
80 Both	Rsea	7	94	11.88	0.98	0.171	3.80	0.671	0.819	0.215
82 DSJ	All Data	5	72	8.10	0.44	0.124	1.68	0.259	0.509	0.303
83 DSJ	All Data	7	50	8.45	1.08	0.237	4.36	1.462	1.209	0.277
83 DSJ	Csea	7	21	2.75	0.84	0.340	9.92	17.813	4.221	0.425
83 DSJ	Rsea	6	31	7.60	1.06	0.254	3.10	1.131	1.063	0.343

Table 5. Absolute density estimates for ship data using detection rates, relative density estimates and LT density estimates.

Area	Density ($\hat{D}$) (Schools/ 1000 km^2)	S.E. ($\hat{D}$)	C.V. ($\hat{D}$) (%)
Offshore			
LT Estimate	2.04	0.263	12.9
Relative Density	2.39	0.621	26.0
7.4-km Truncated Detection Rates	2.11	0.459	21.8
2.1-km Truncated Detection Rates	2.16	0.480	22.2
Inshore			
LT Estimate	4.47	0.514	11.5
Relative Density	6.88	1.901	42.5
7.4-km Truncated Detection Rates	6.49	1.422	21.9
2.1-km Truncated Detection Rates	6.36	1.441	22.7
All Areas			
LT Estimate	2.95	0.253	8.6
Relative Density	4.04	1.023	25.3
7.4-km Truncated Detection Rates	3.75	0.780	20.8
2.1-km Truncated Detection Rates	3.74	0.790	21.1

Table 6. Unadjusted inshore and offshore density estimates for data with maximum Beaufort states of 4 and of 3 and adjusted inshore and offshore density estimates for data with maximum 5, 4 and 3 Beaufort states.

	Unadjusted Estimate				Adjusted Estimate					
	4		3		5		4		3	
Area	Density ($\hat{D}$) (Schools/ 1000 km^2)	S.E. ($\hat{D}$)	Density ($\hat{D}$) (Schools/ 1000 km^2)	S.E. ($\hat{D}$)	Density ($\hat{D}$) (Schools/ 1000 km^2)	S.E. ($\hat{D}$)	Density ($\hat{D}$) (Schools/ 1000 km^2)	S.E. ($\hat{D}$)	Density ($\hat{D}$) (Schools/ 1000 km^2)	S.E. ($\hat{D}$)
Inshore (Aerial)	4.58	0.81	5.55	1.06	5.23	1.65	5.54	1.68	7.37	2.44
Offshore (Ship)										
Relative Density	2.70	0.67	2.93	0.75	3.05	0.87	3.14	0.86	3.34	0.89
7.4-km Truncated Detection Rates	2.18	0.43	2.44	0.50	2.76	0.69	2.67	0.61	2.83	0.66
2.1-km Truncated Detection Rates	2.26	0.46	2.62	0.55	2.83	0.71	2.95	0.73	3.03	0.72

Table 7. Proportion of total distance searched by ships in each area during each year and proportion of square km in each area.

	Total Area	Offshore Area		Inshore Area		Calibration Area		
Year	Distance Searched (km)	Distance Searched (km)	% Total km Searched	Distance Searched (km)	% Total km Searched	Distance Searched (km)	% Total km Searched	% Inshore km Searched
1977	26151	22423	86	3728	14	0	-	0
1979	17723	6386	36	11337	64	9776	55	86
1980	14902	8456	57	6447	43	2930	20	45
1982	9444	6066	64	3378	36	2617	28	77
1983	6186	3236	52	2950	48	1521	25	56
Total	74406	46567	63	27840	37	16844	23	61

Total Area[a]	Offshore Area[a]		Inshore Area[a]		Calibration Area[b]		
km^2	km^2	% Total Area	km^2	% Total Area	km^2	% Total Area	% Inshore Area
19,270,232	13,267,763	69	6,002,469	31	2,636,694	13	44

[a] Source: Holt and Powers (1982)
[b] Source: Approximation determined by counting 1° squares in area

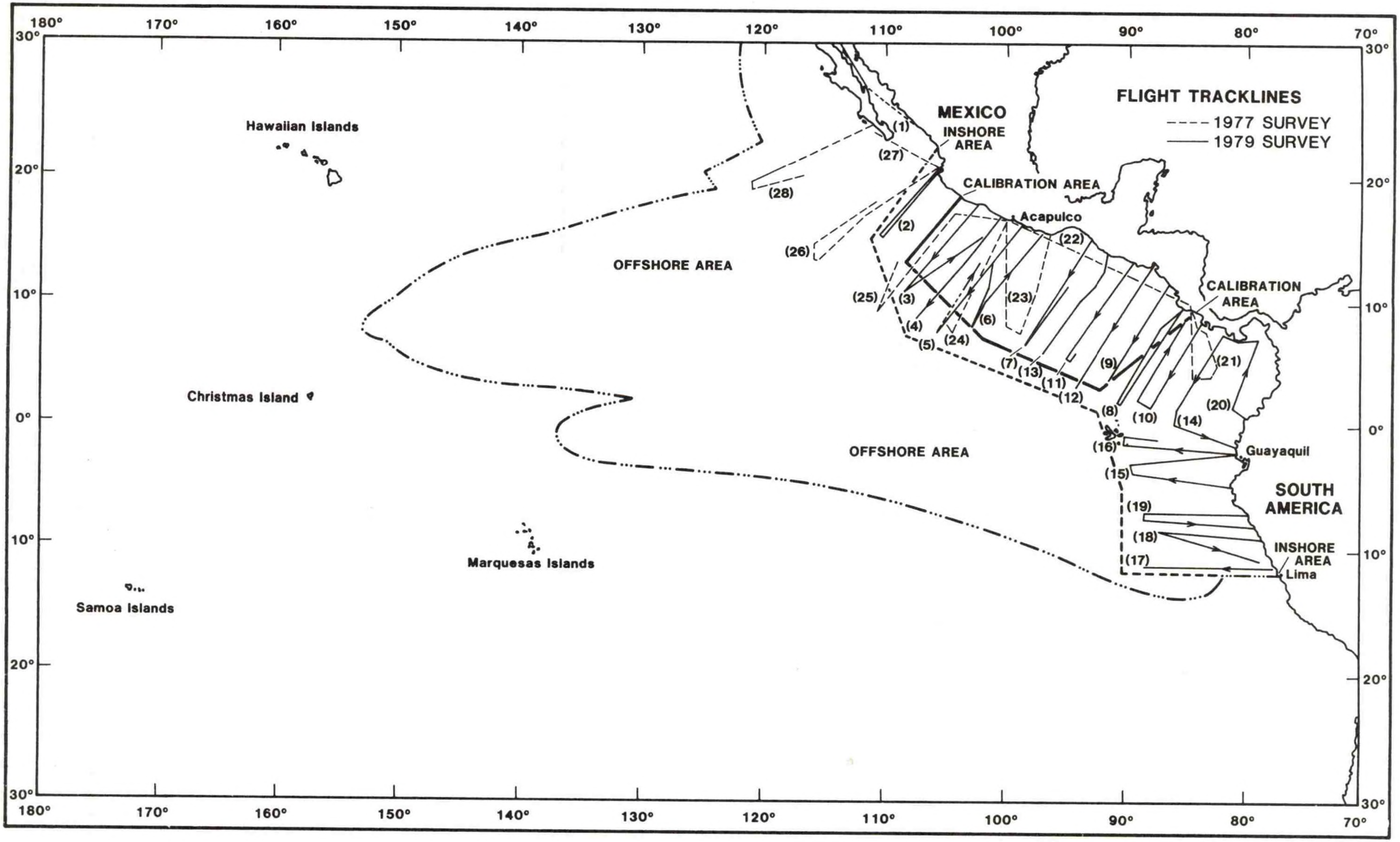


Figure 1. Tracklines for 1977 and 1979 aerial surveys.

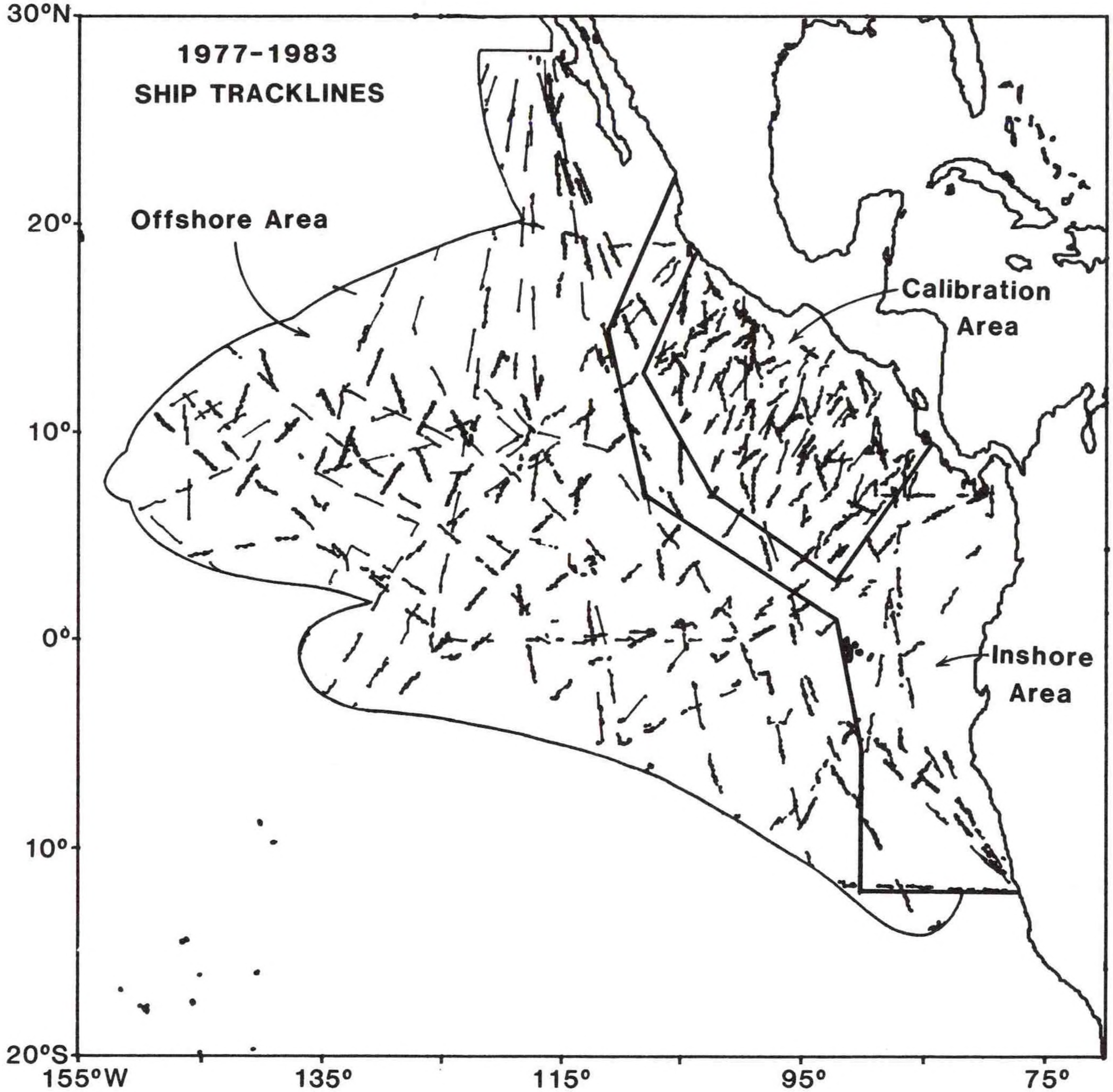


Figure 2. Tracklines for combined 1977, 1979, 1980, 1982, and 1983 ship surveys.

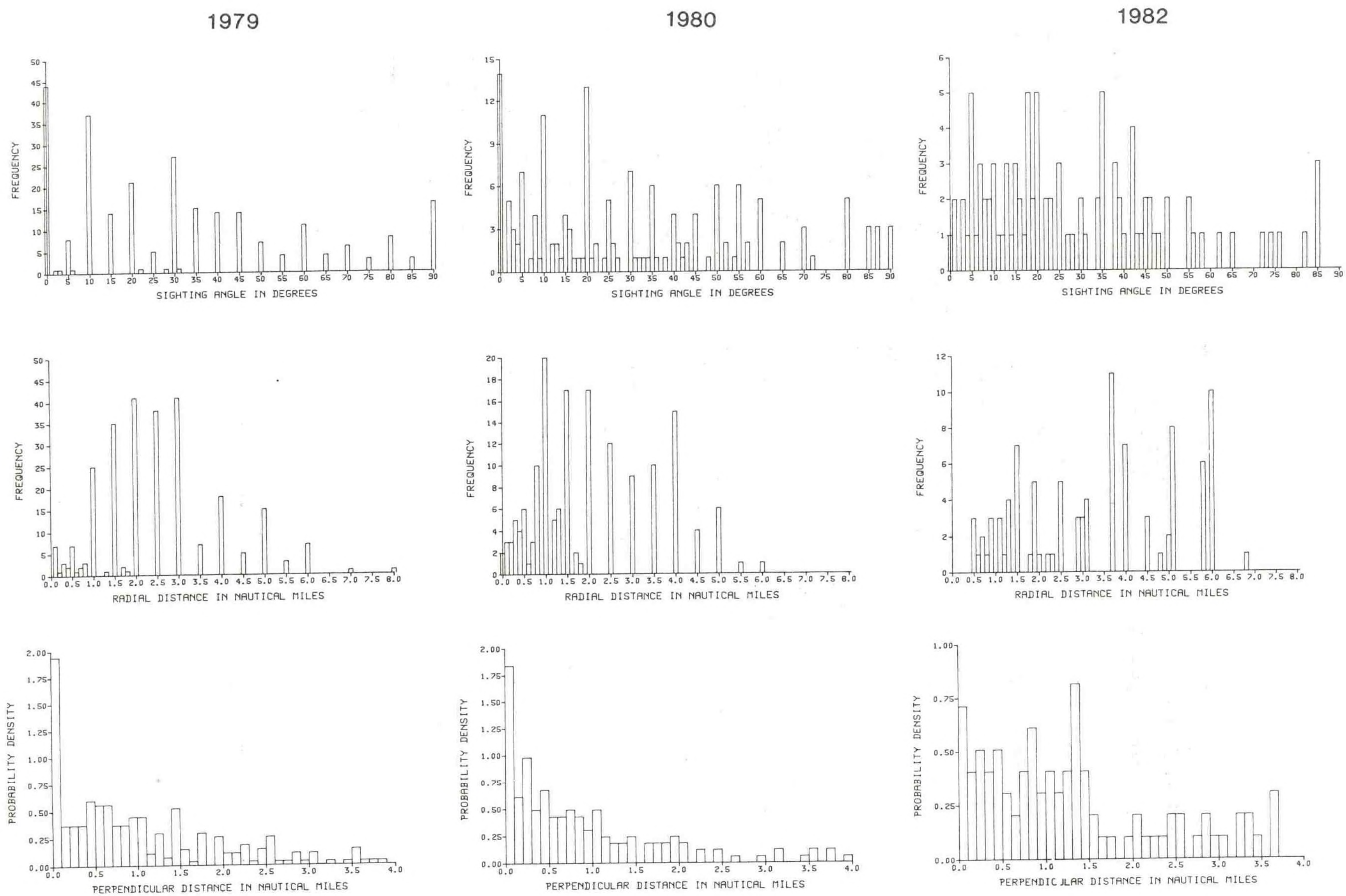


Figure 3. Distribution of sighting angle, radial distance, and perpendicular distance for 1979, 1980, and 1982 ship data.

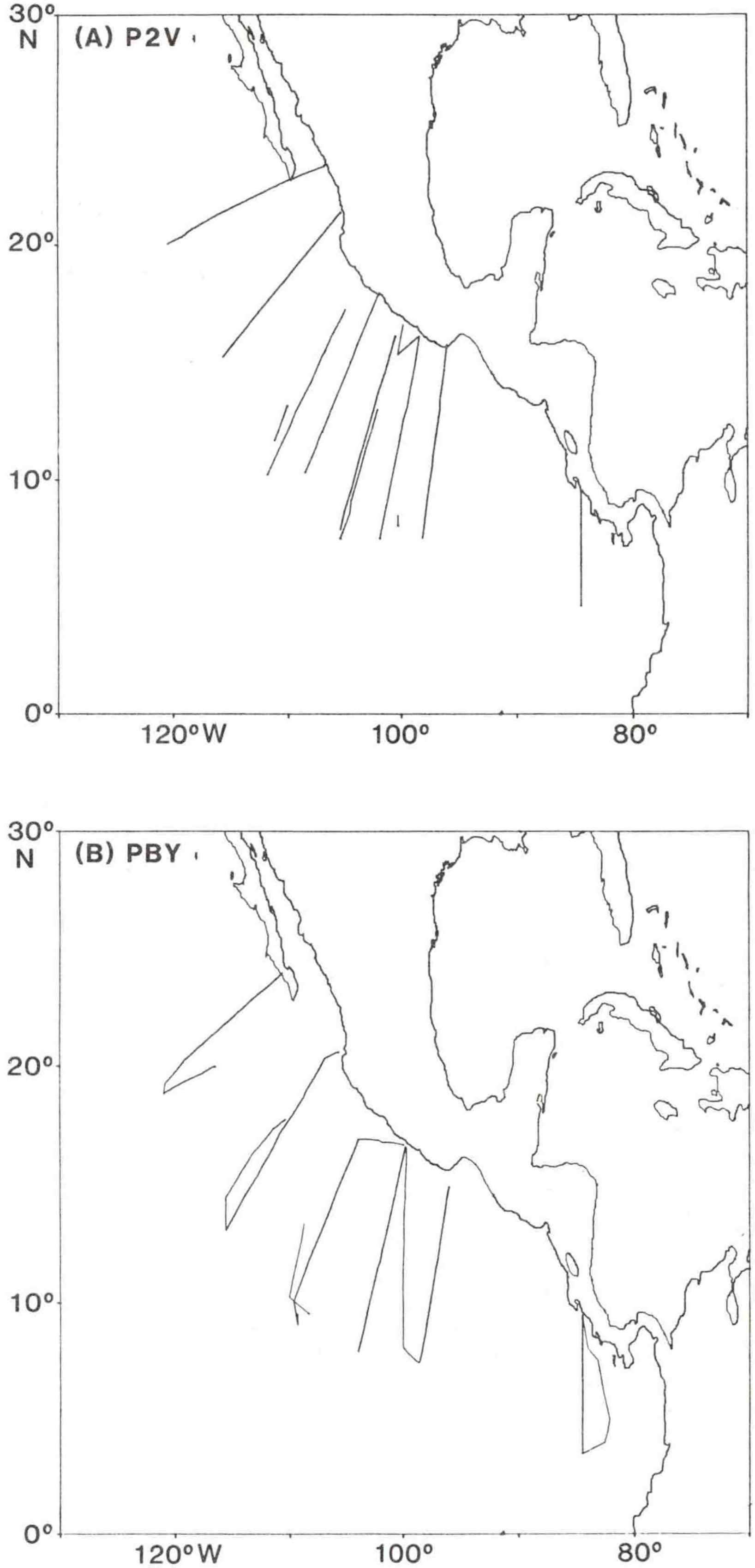


Figure 4. Overlapping tracklines surveyed by the P2V(A) and PBY(B) airplanes in 1977 and used in analysis of aircraft effect.

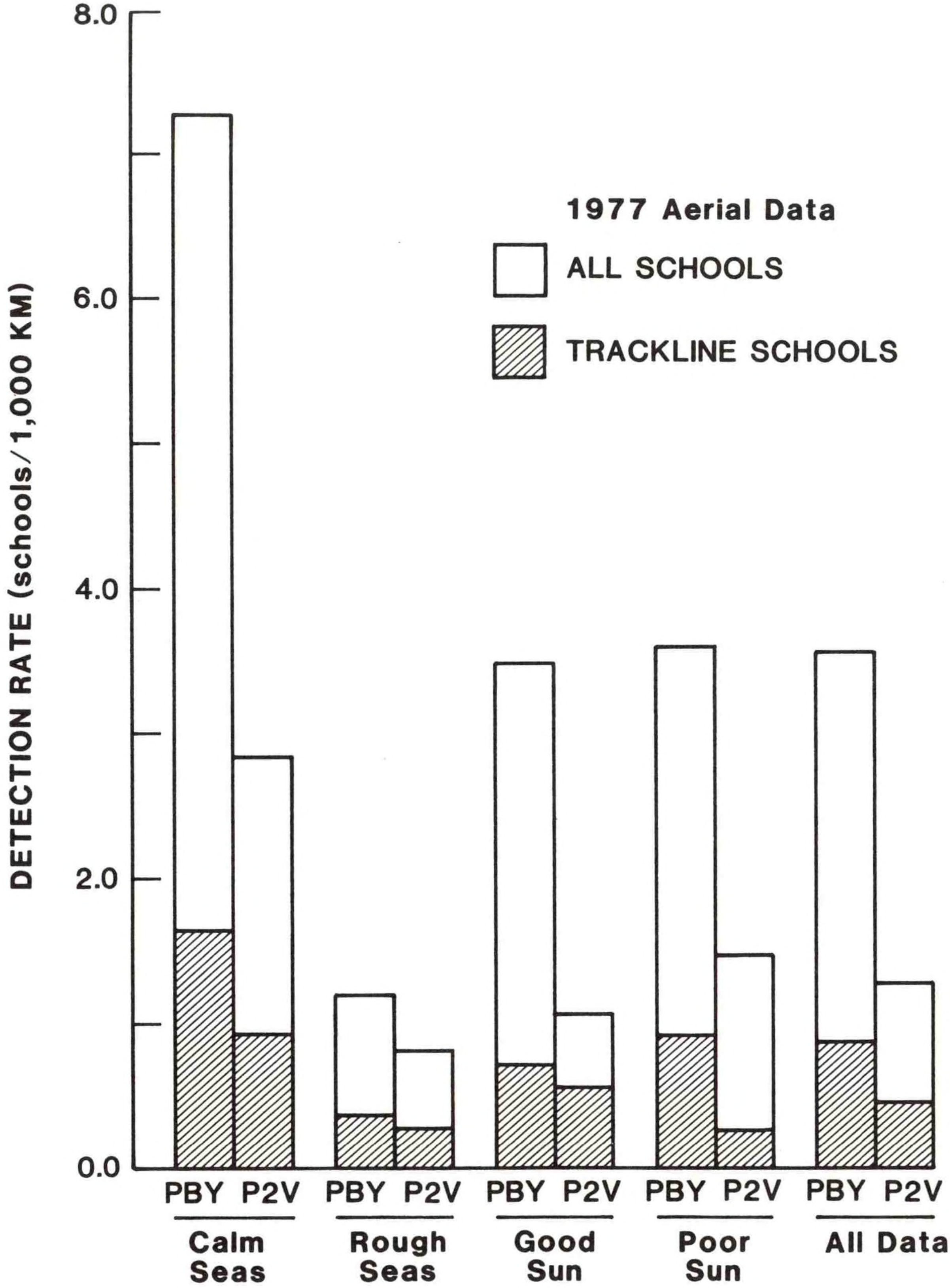


Figure 5. Detection rates from P2V and PBY airplanes stratified by sea state and sun glare categories for approximately overlapping searching effort.

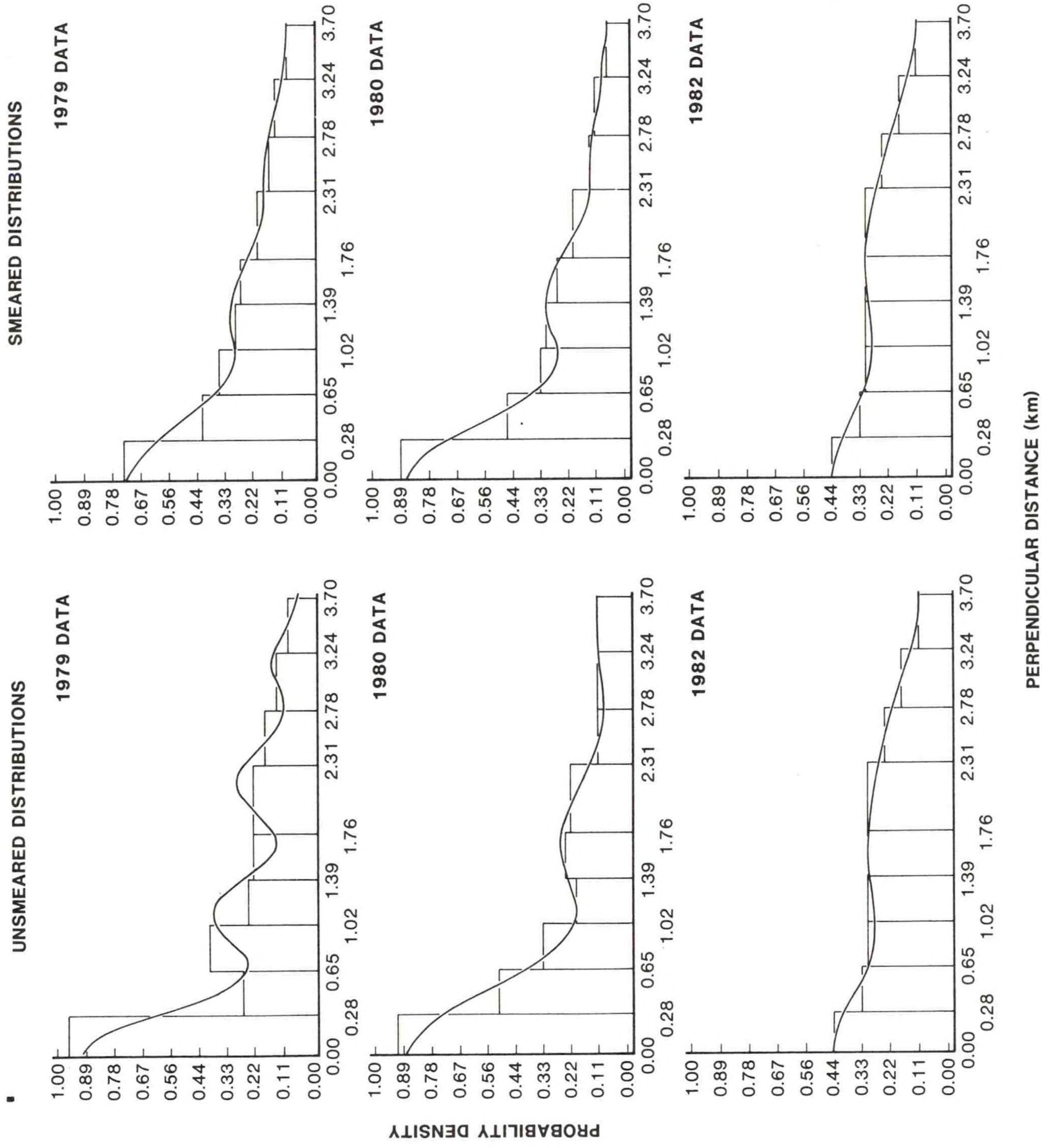


Figure 6. Fit of Fourier series model for smeared and unsmeared perpendicular distance data for 1979, 1980, and 1982 from ships.

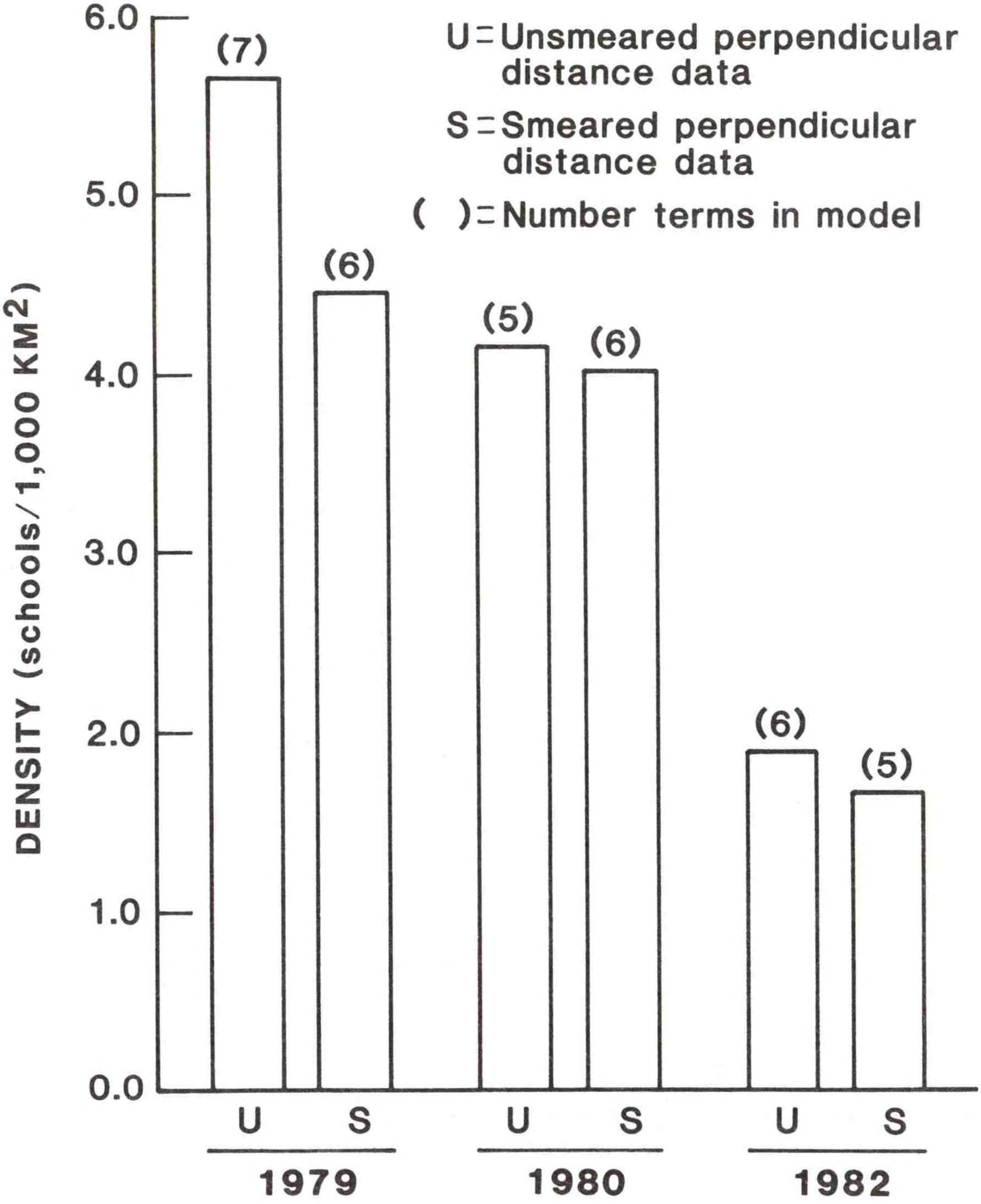


Figure 7. Relative school density estimates for smeared and unsmeared perpendicular distance data for 1979, 1980 and 1982 from ships.

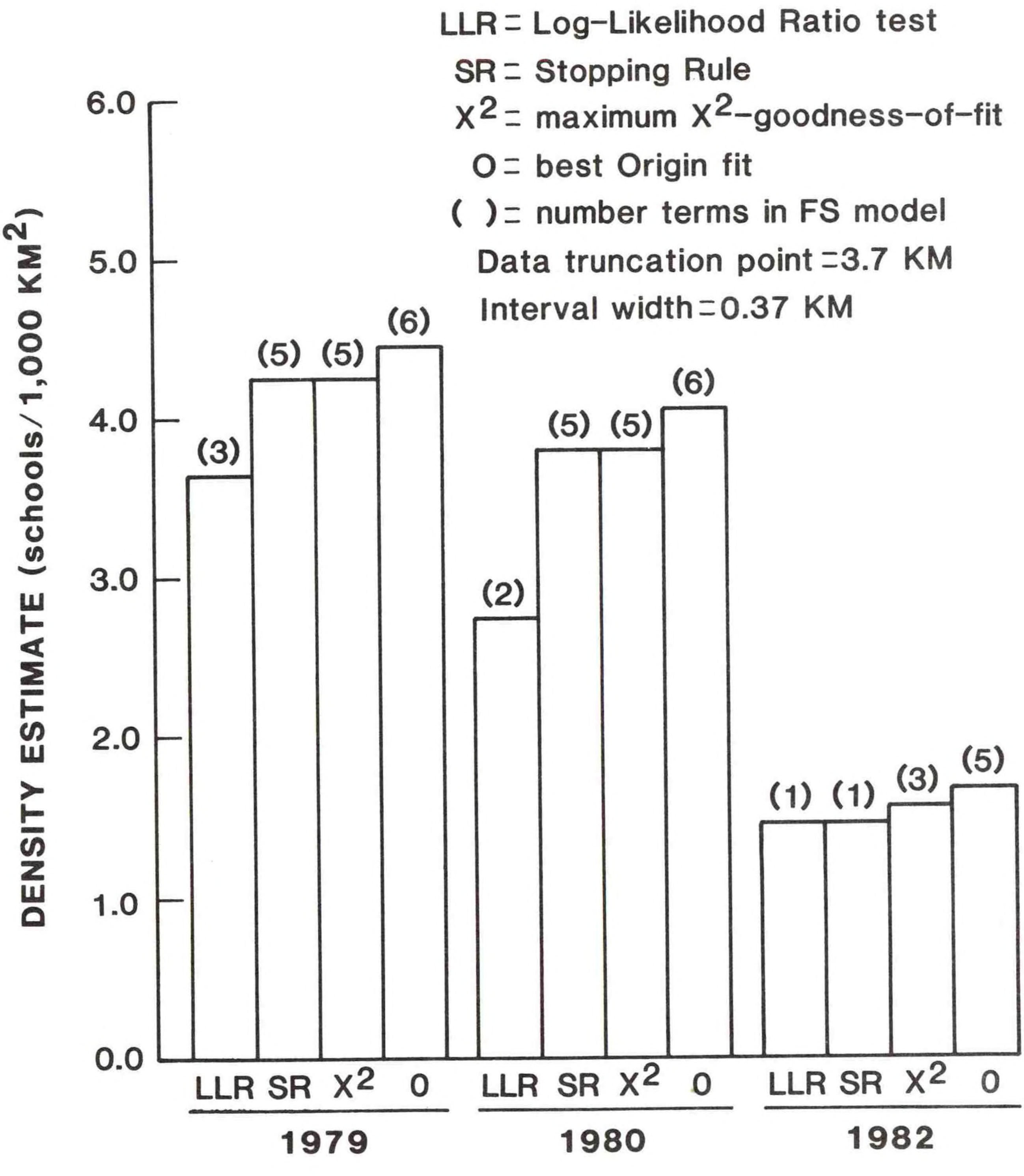


Figure 8. Relative school density estimates for ship survey data using various criteria to select best fit of the Fourier Series (FS) model.

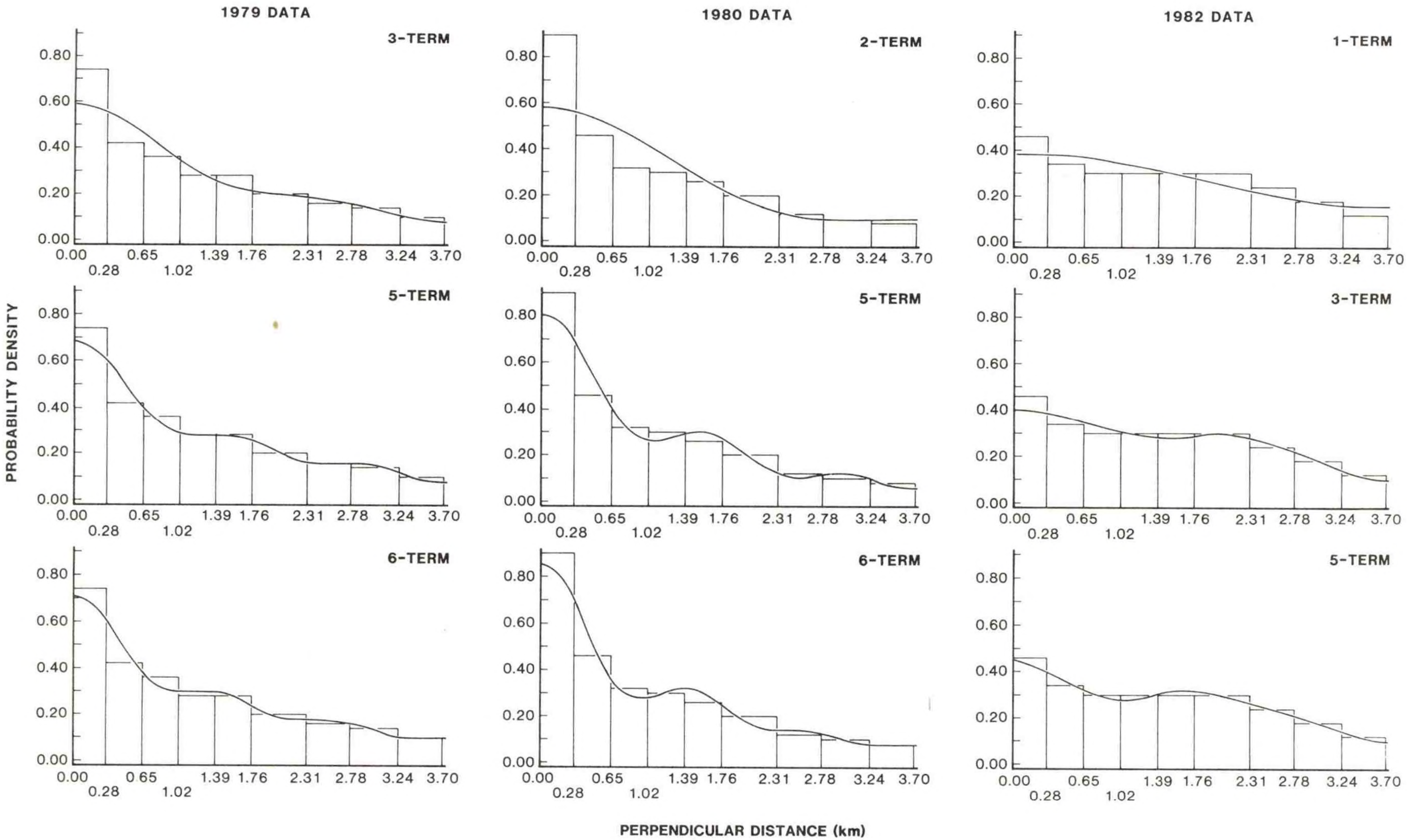


Figure 9. Fit of Fourier series model with different number of terms. Ship survey data for 1979, 1980, and 1982 are used.

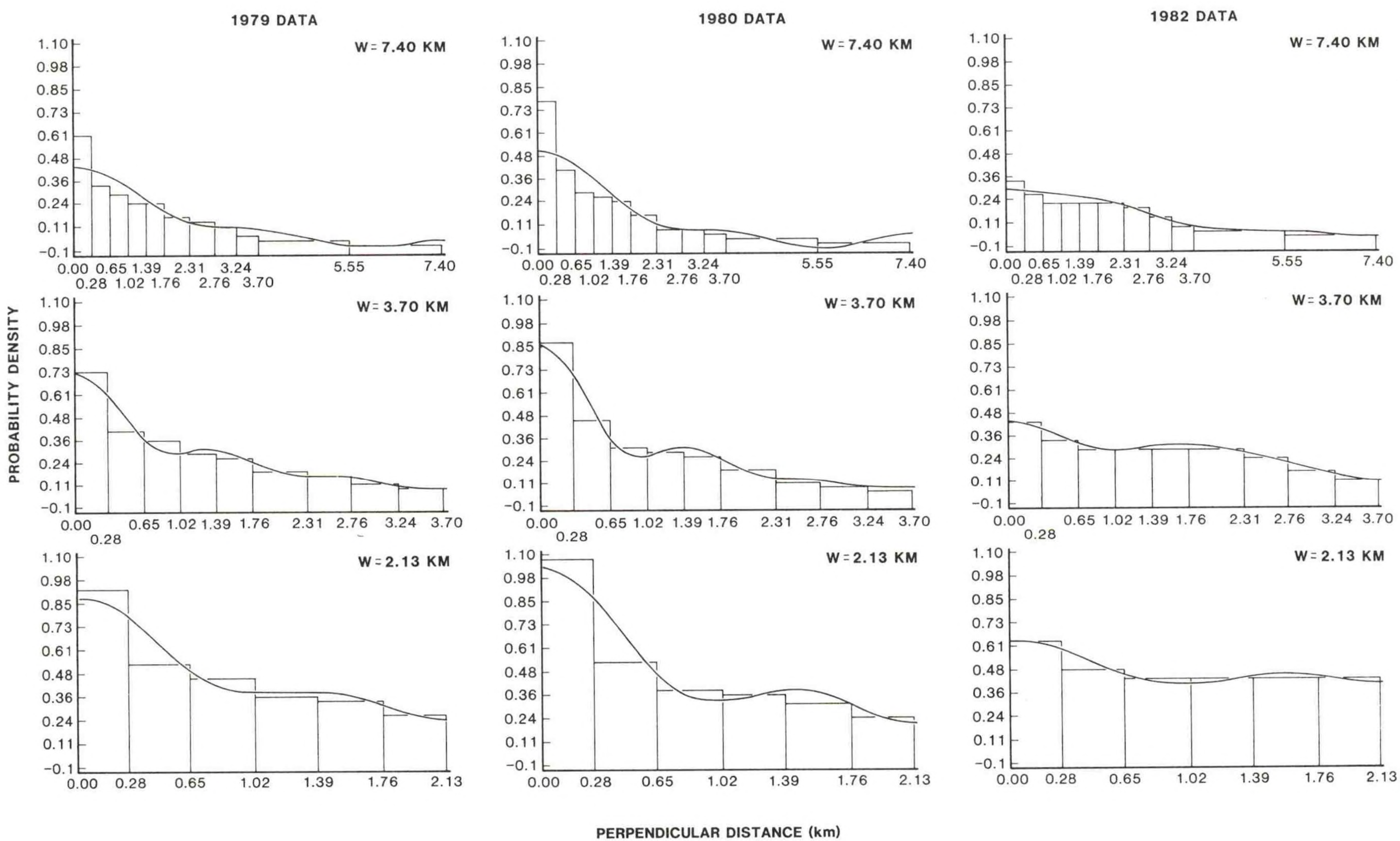


Figure 10. Fit of Fourier series model with data from ship surveys truncation at 7.4, 3.7, and 2.1 km.

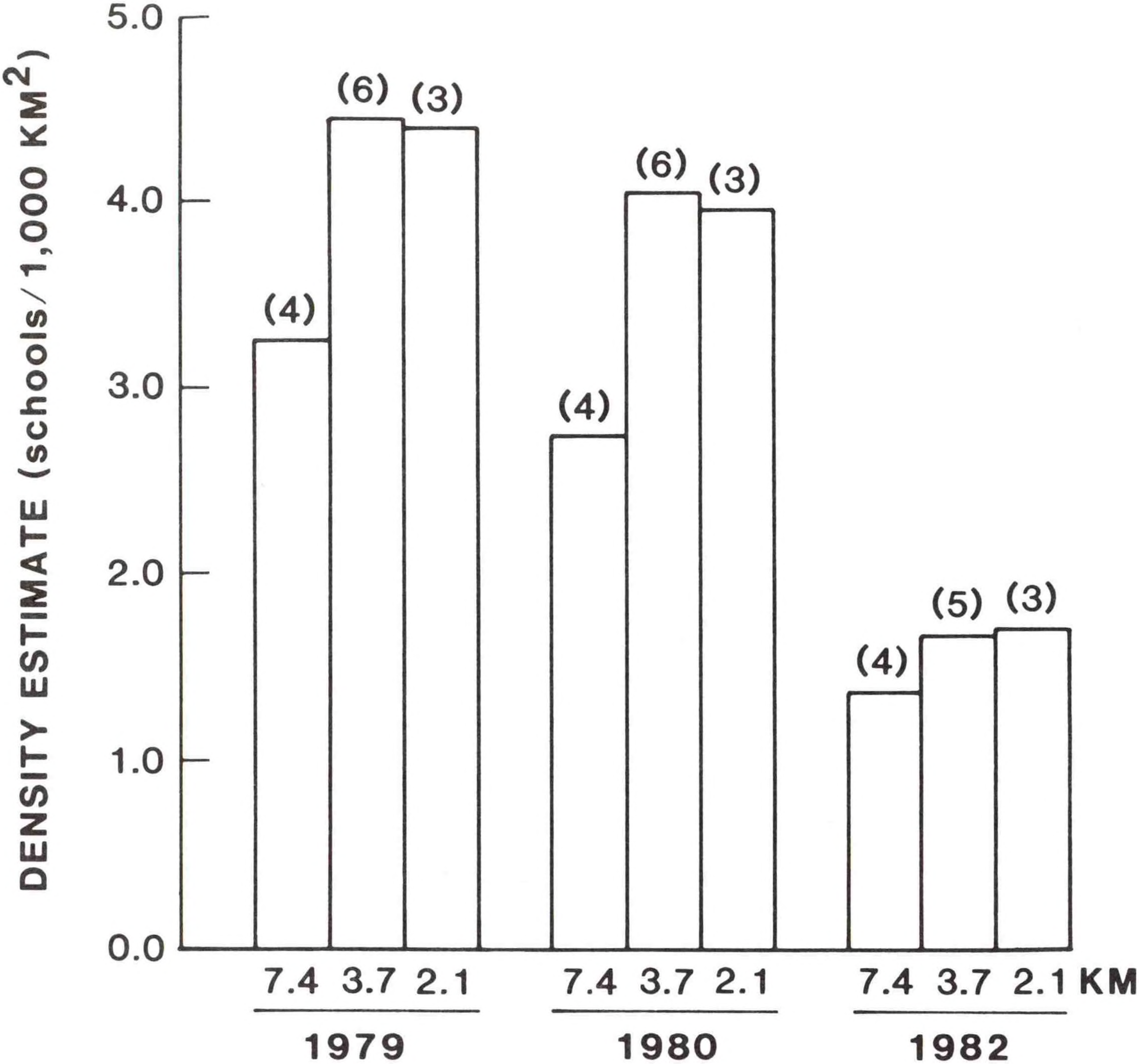


Figure 11. Relative school density estimates for 1979, 1980, and 1982 for data from ship surveys truncated at 7.4, 3.7, and 2.1 km. The number of terms used to fit the Fourier series model appears in parentheses.

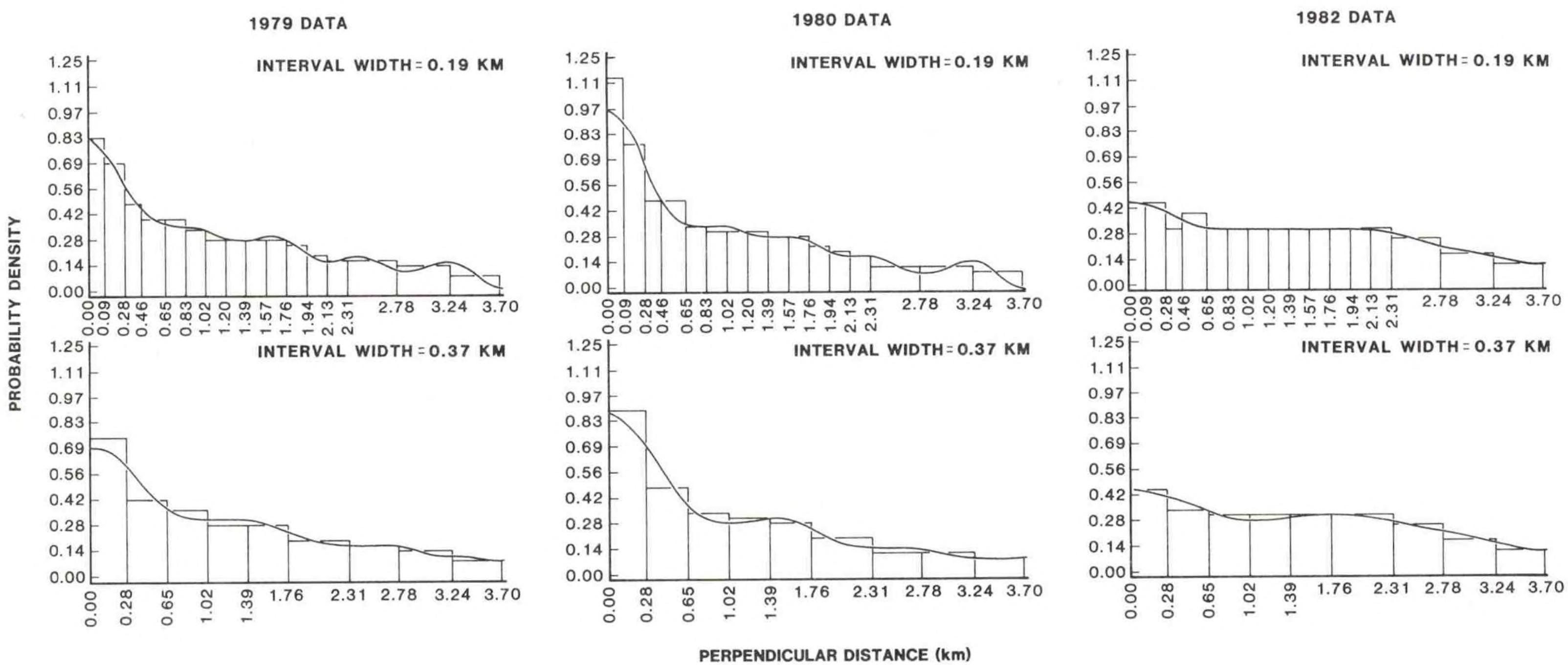


Figure 12. Fit of Fourier series model for perpendicular distance data grouped into units with widths of 0.19 and 0.37 km. Data were collected during ship surveys in 1979, 1980, and 1982.

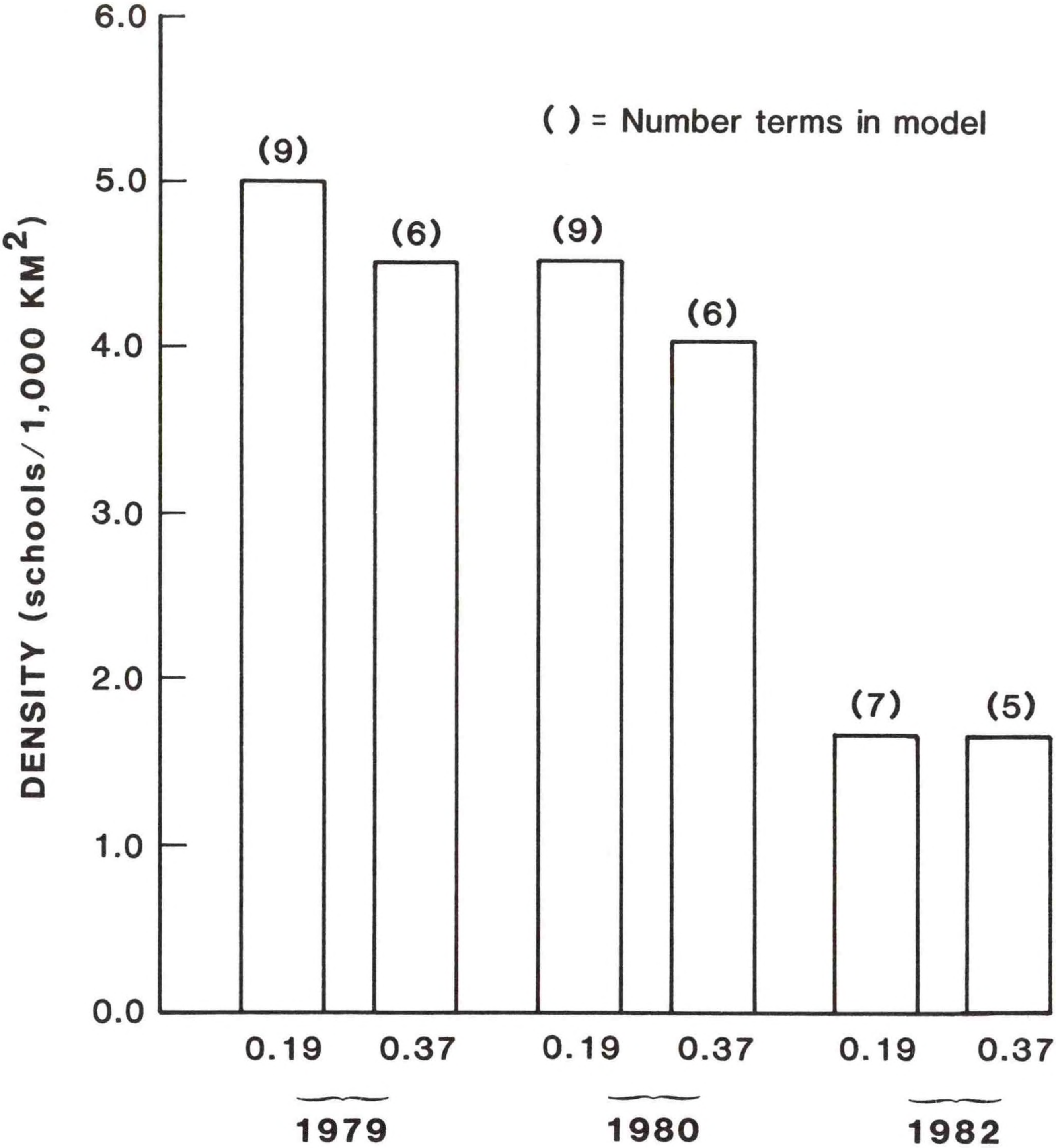


Figure 13. Relative school density estimates for 1979, 1980, and 1982 for data from ship surveys grouped into approximate interval widths of 0.19 and 0.37 km.

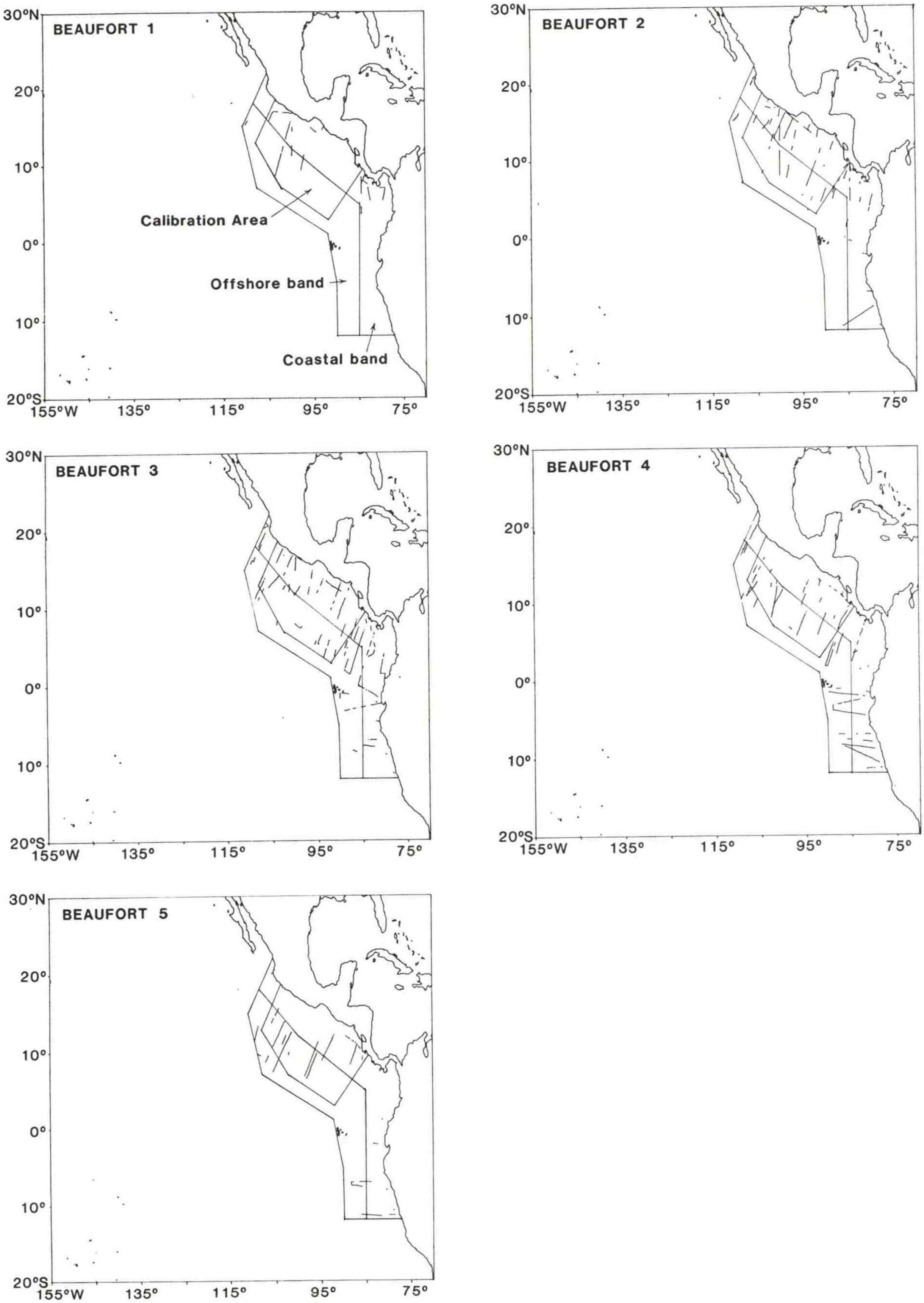
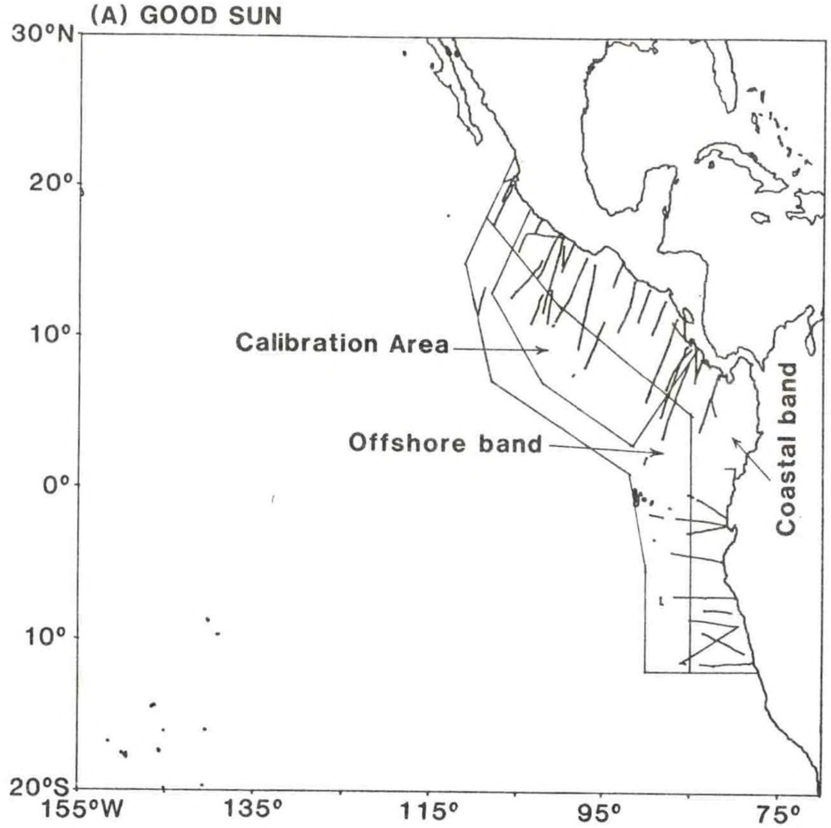


Figure 14. Tracklines surveyed by the PBY aircrafts in 1977 and 1979 in the coastal and offshore bands stratified by Beaufort state.



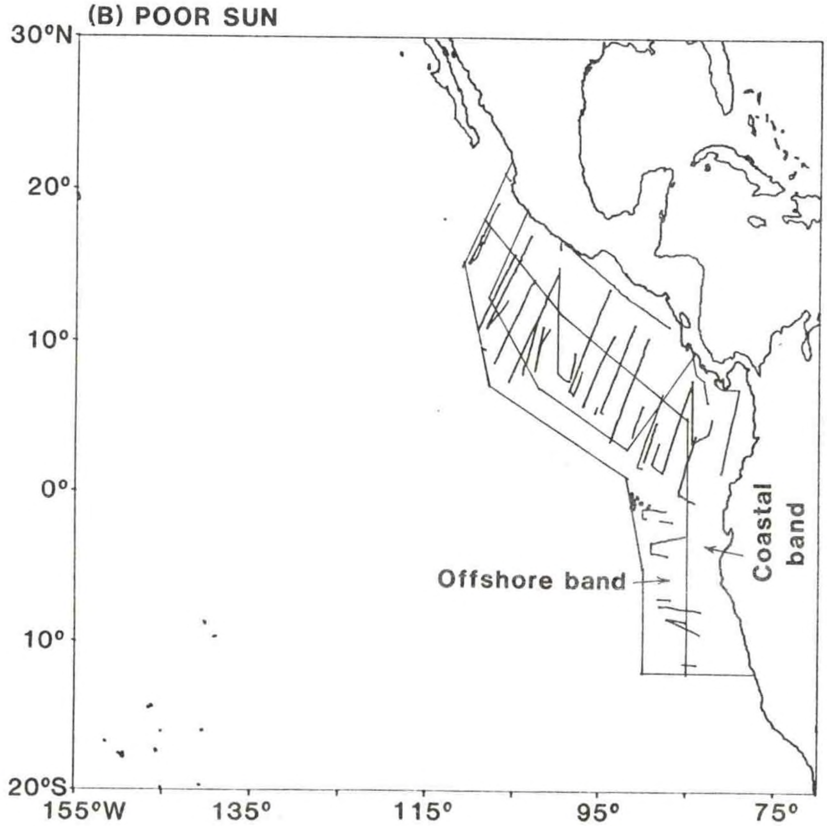


Figure 15. Tracklines surveyed by the PBY aircrafts in 1977 and 1979 during good (A) and poor (B) sun glare conditions in the coastal and offshore bands.

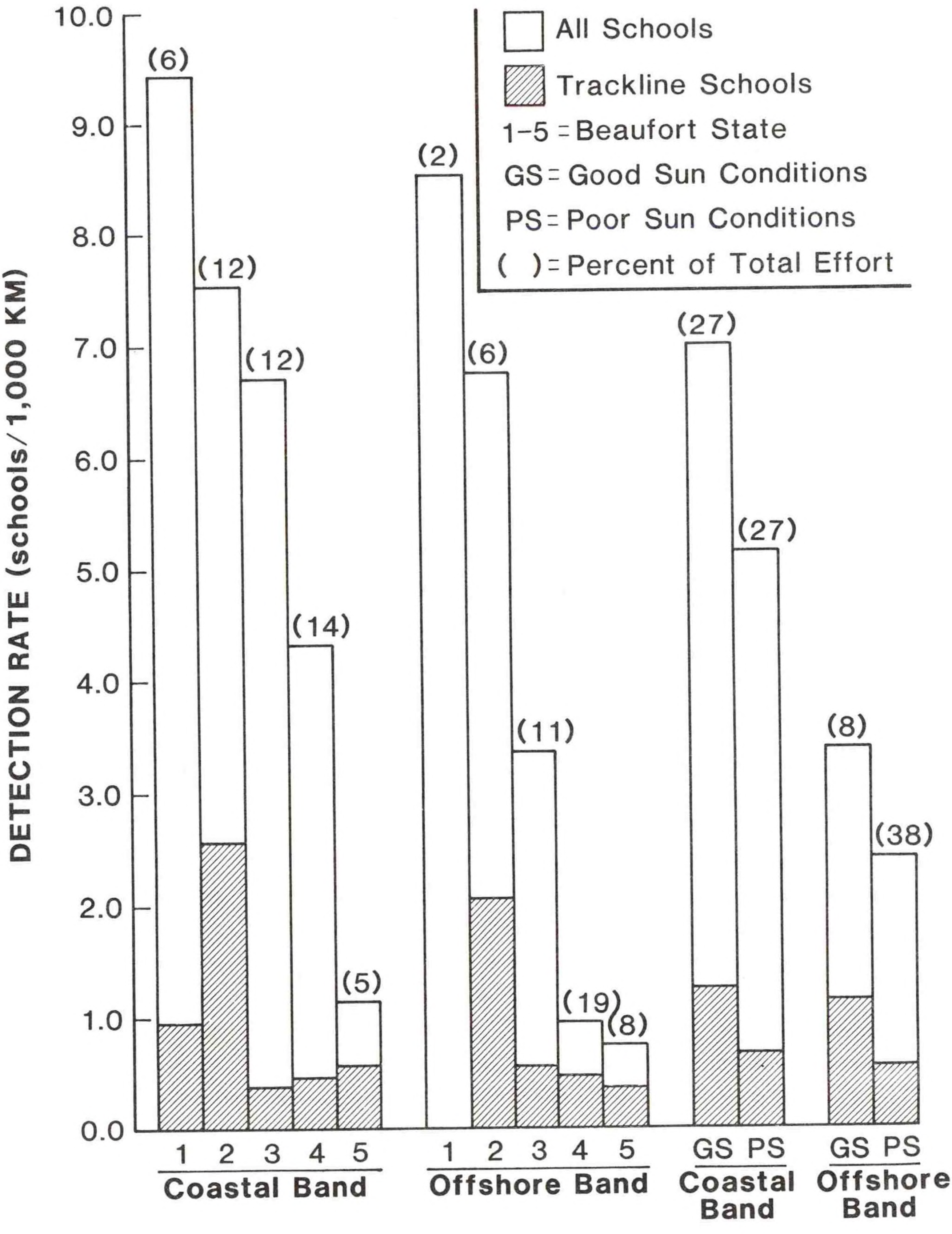


Figure 16. School detection rates in the coastal (c) and offshore (o) bands by sea state and sun glare categories. Aircraft (PBY) survey data for 1977 and 1979 are used.

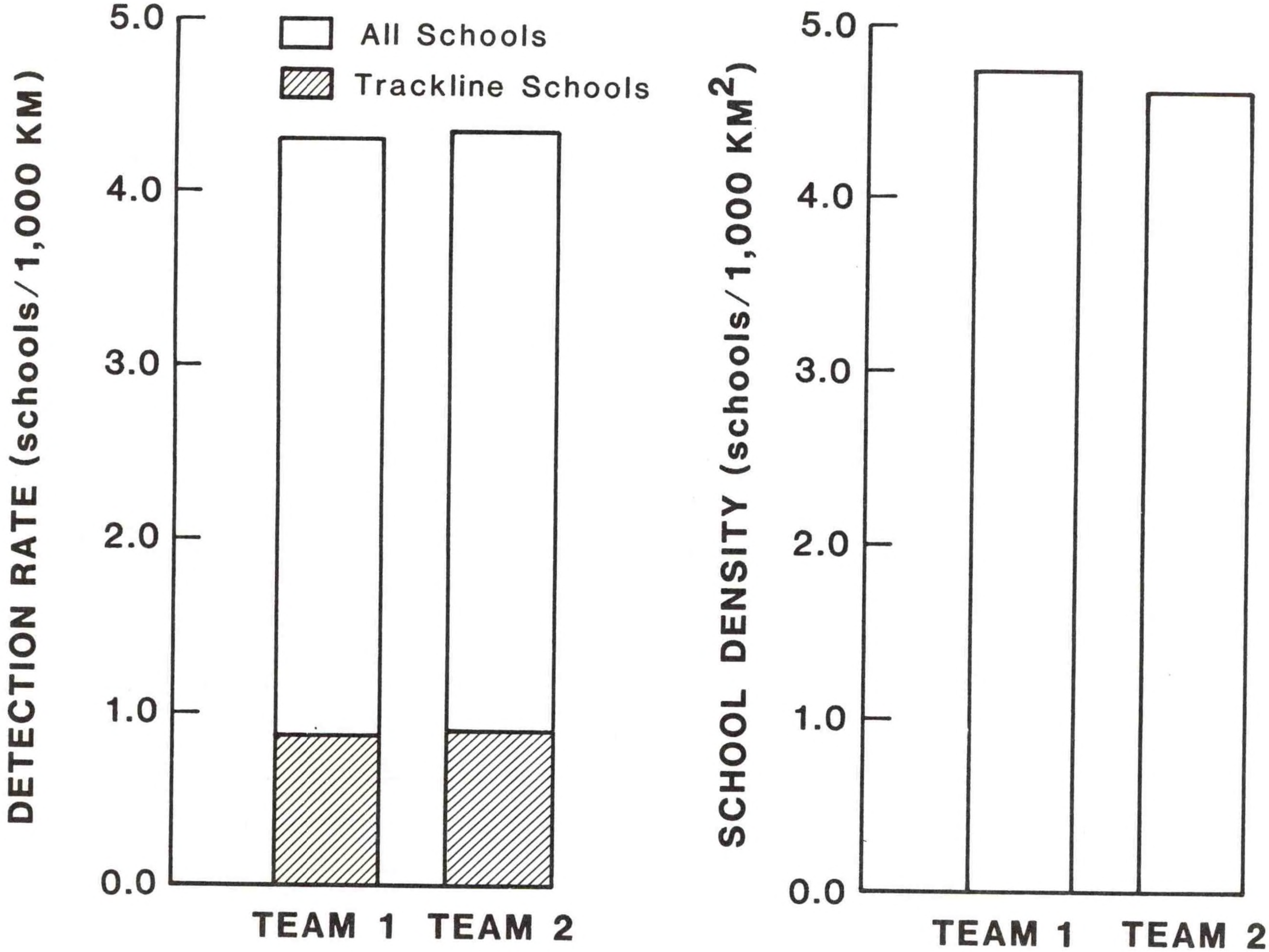


Figure 17. School detection rates and density estimates for observer teams participating in the 1979 aerial survey.

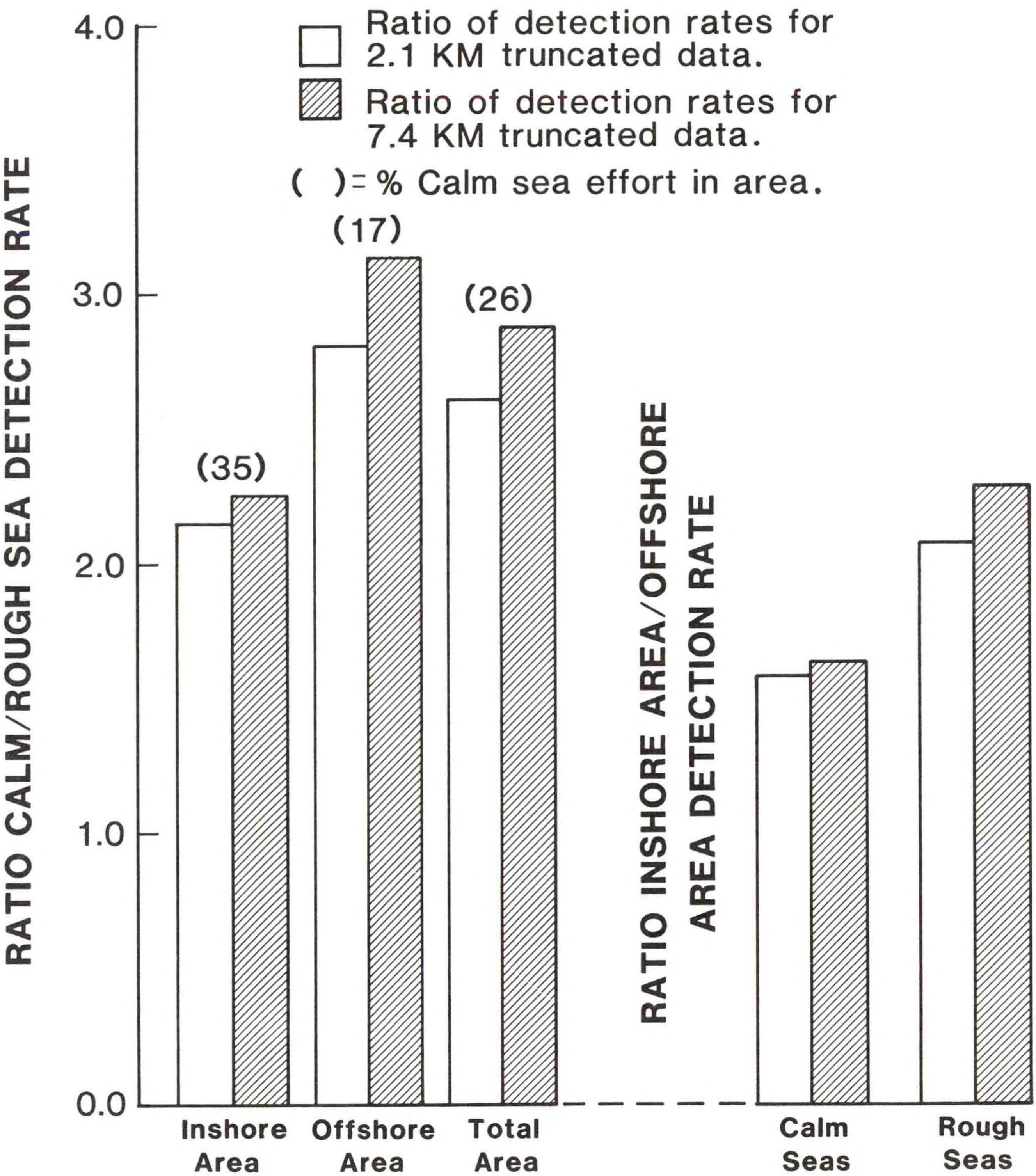


Figure 18. Ratio of school detection rates for different sea states (calm sea versus rough sea) and area (inshore versus offshore). Detection rates computed with perpendicular distance data truncated at 2.1 and 7.4 km.

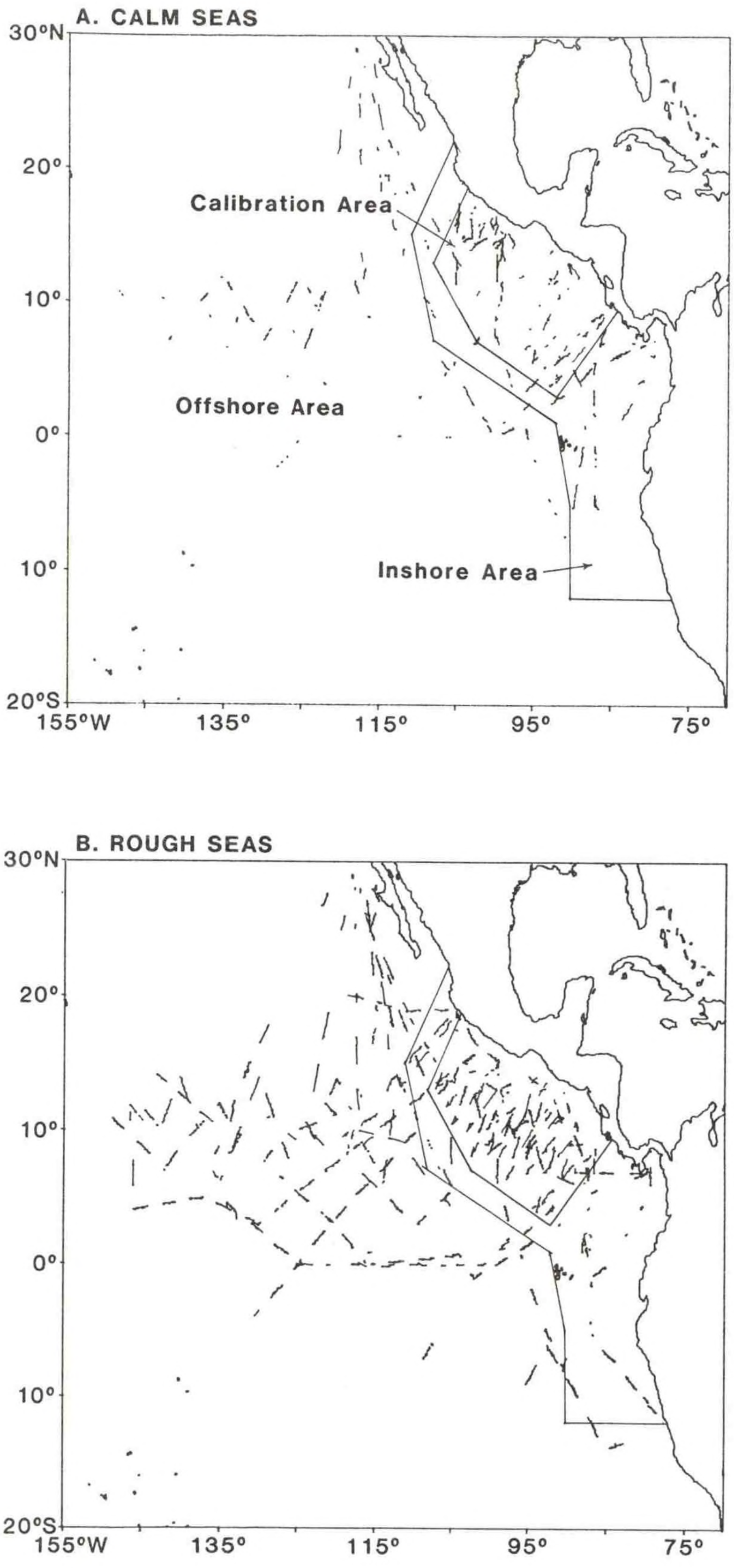


Figure 19. Distribution of searching effort for the 1973-1983 ship surveys during calm (A) and rough conditions (B).

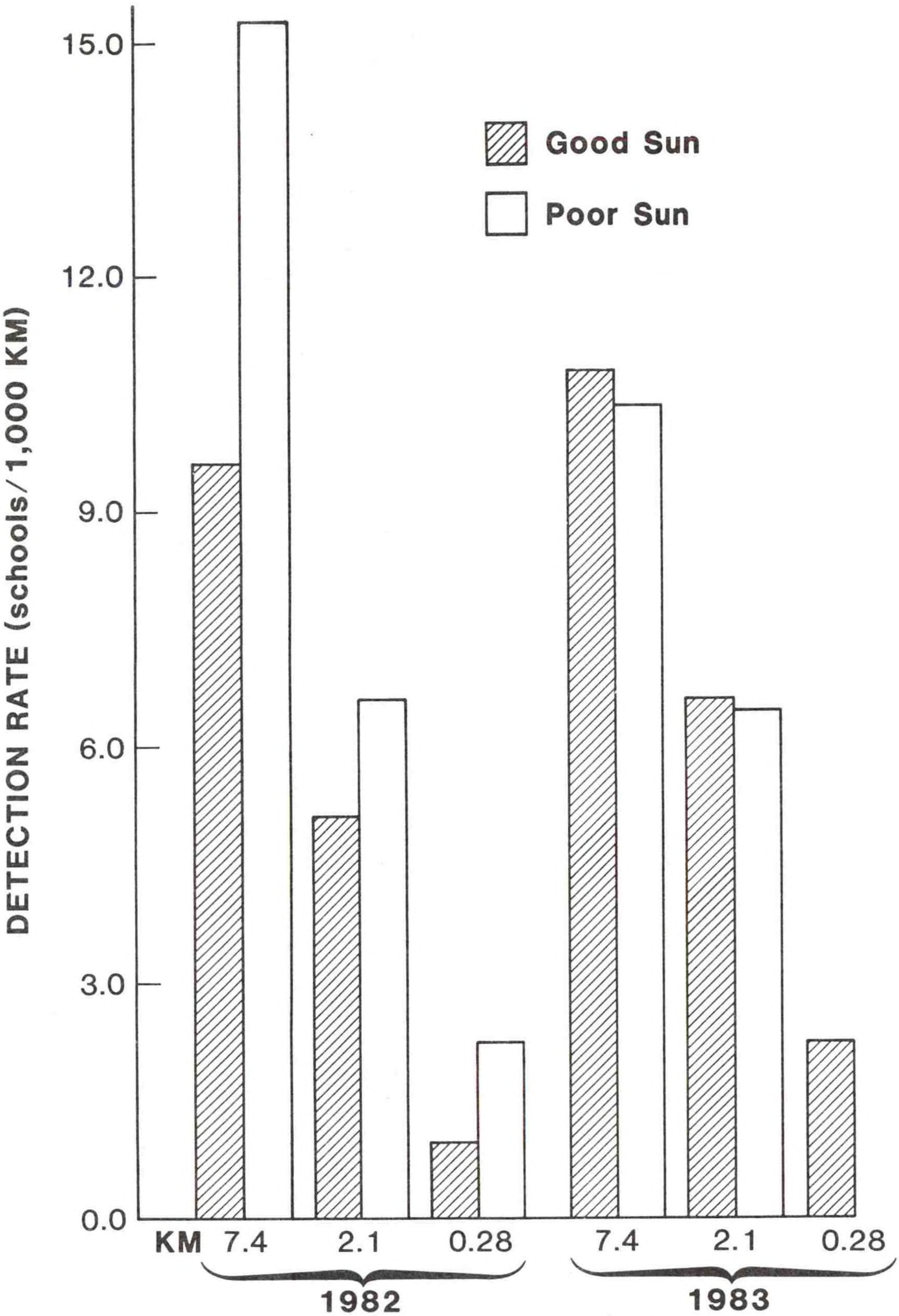


Figure 20. School detection rates and relative density estimates during good (GS) and poor (PS) sun glare conditions for 1982 and 1983 ship survey data.

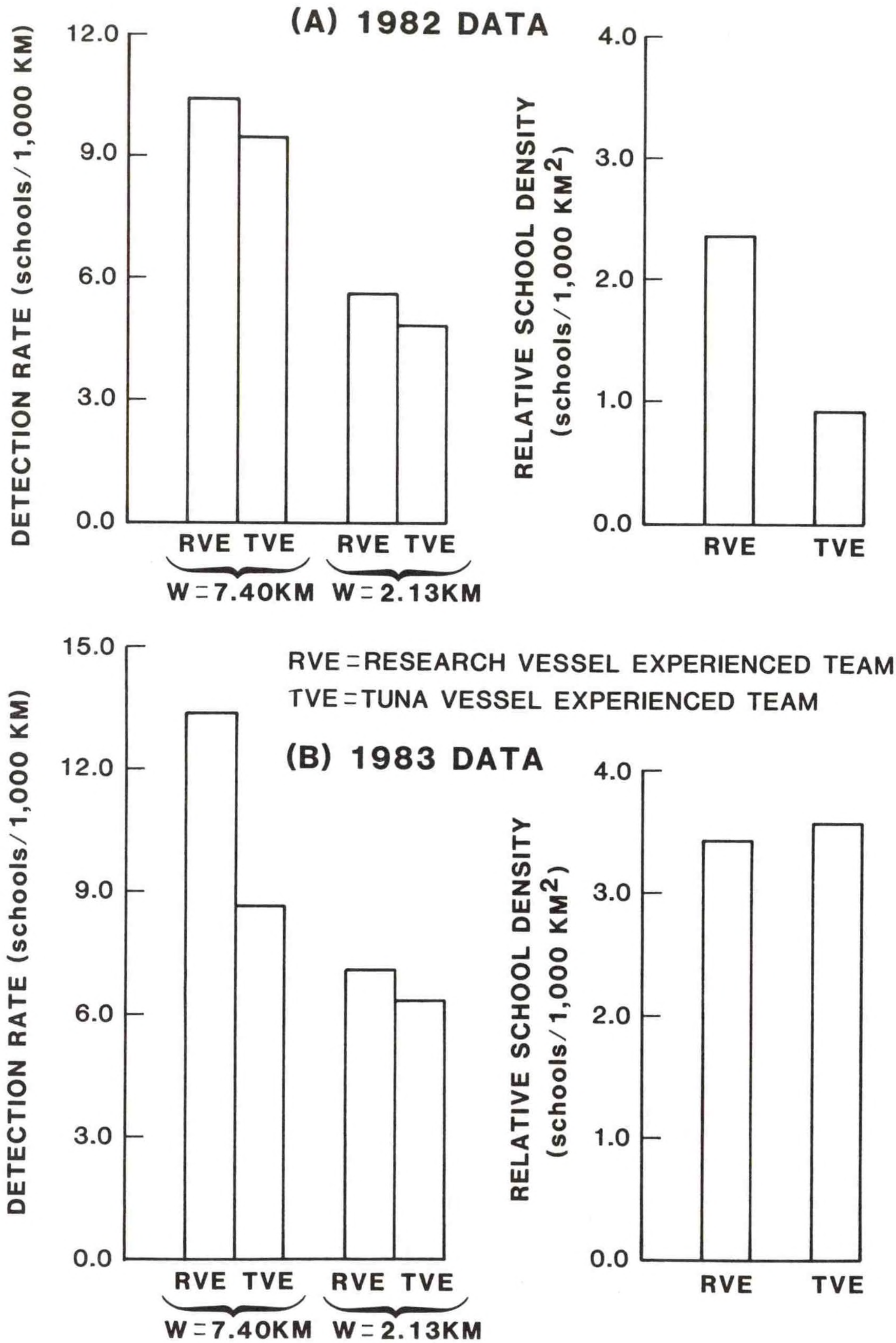


Figure 21. School detection rates and relative density estimates for research vessel experienced (RVE) and tuna vessel experienced (TVE) observer teams participating on the 1982 (A) and 1983 (B) ship surveys.

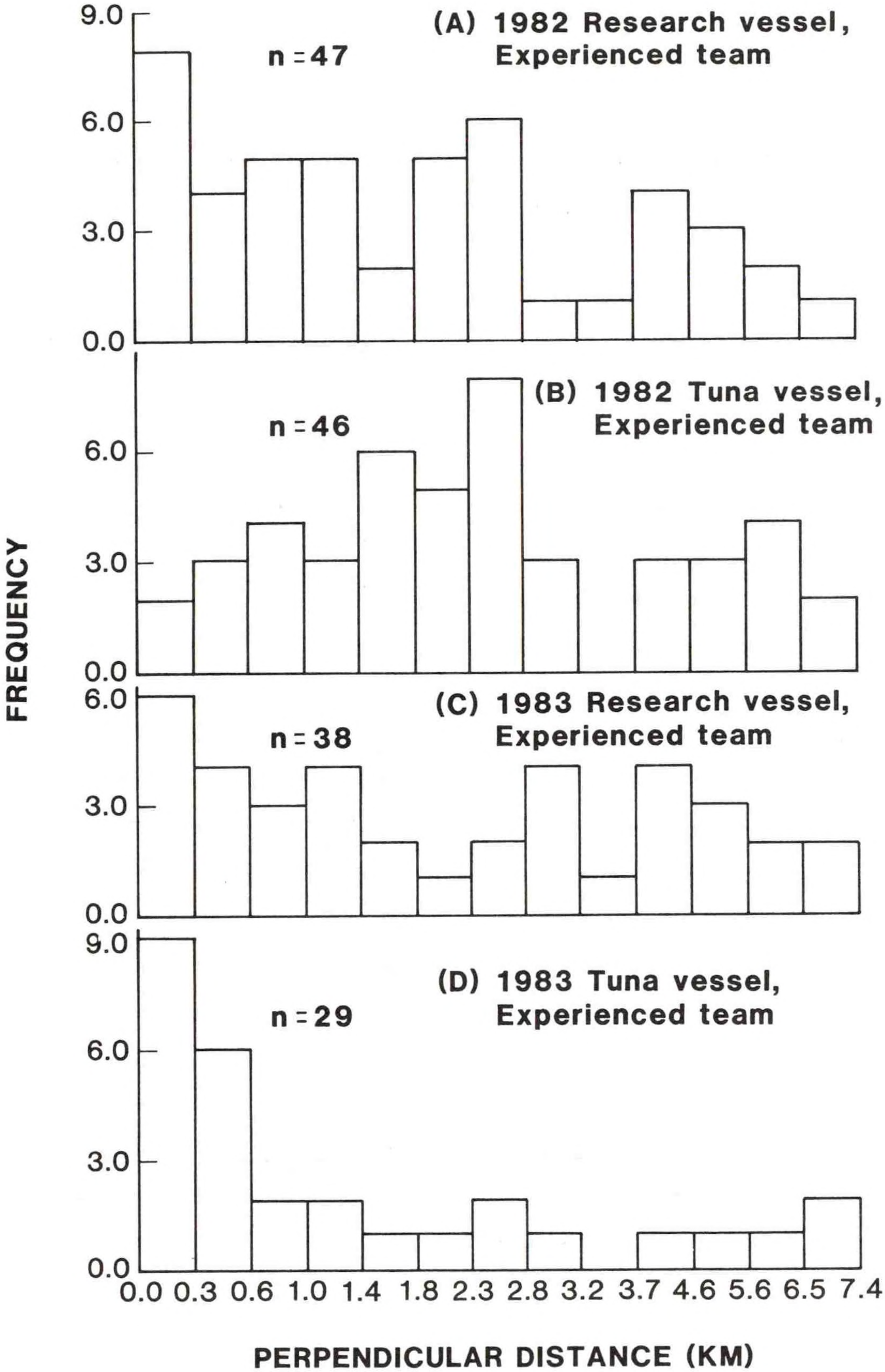


Figure 22. Distribution of perpendicular sighting distances for different observer teams: (A) 1982 research-vessel-experienced, (B) 1982 tuna-vessel-experienced, (C) 1983 research-vessel-experienced, and (D) 1983 tuna-vessel-experienced. The number of schools detected is shown.

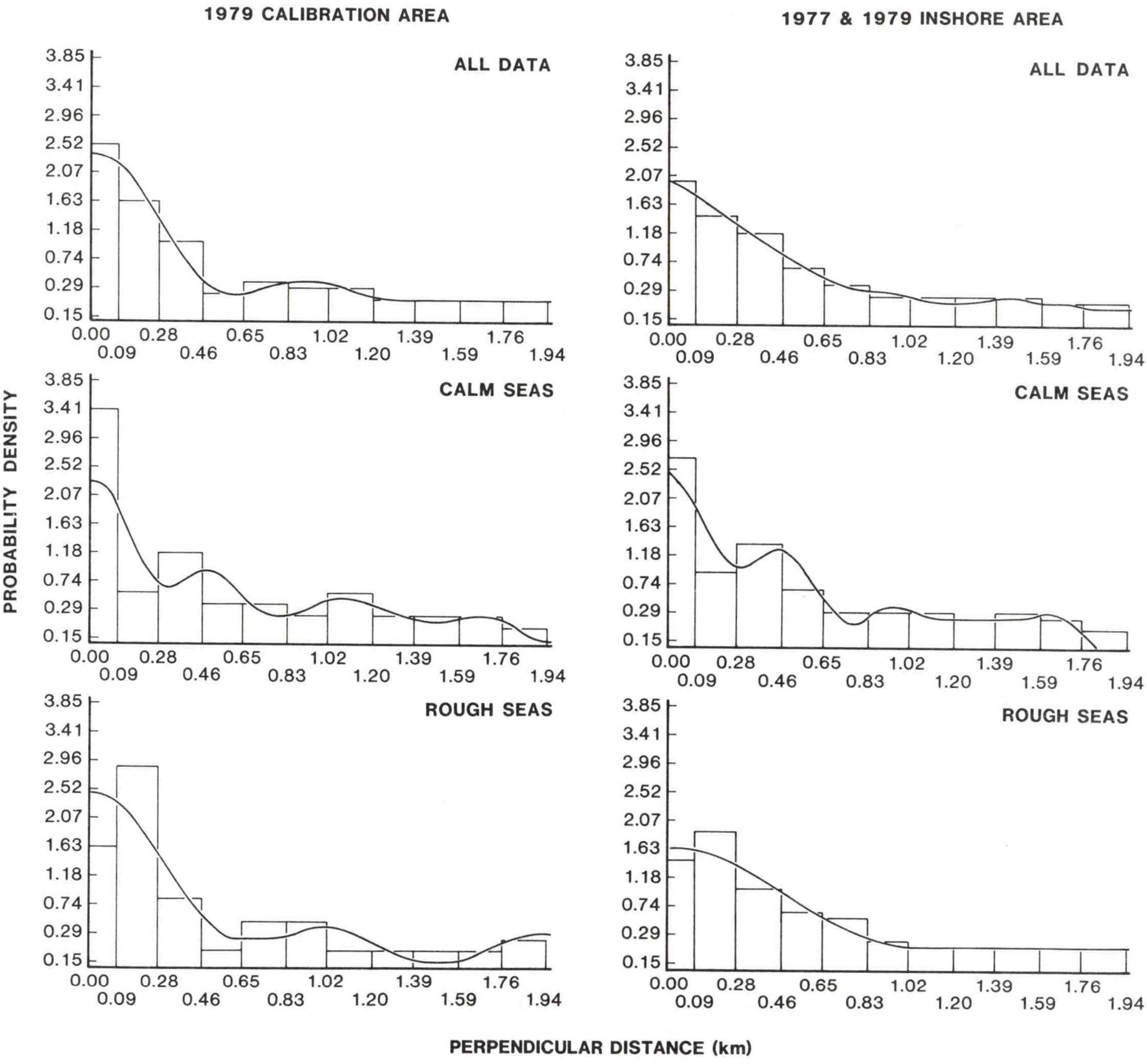


Figure 23. Fit of the Fourier series model to perpendicular distance data collected on the 1977 and 1979 aerial surveys. Data have been stratified by sea state and area.

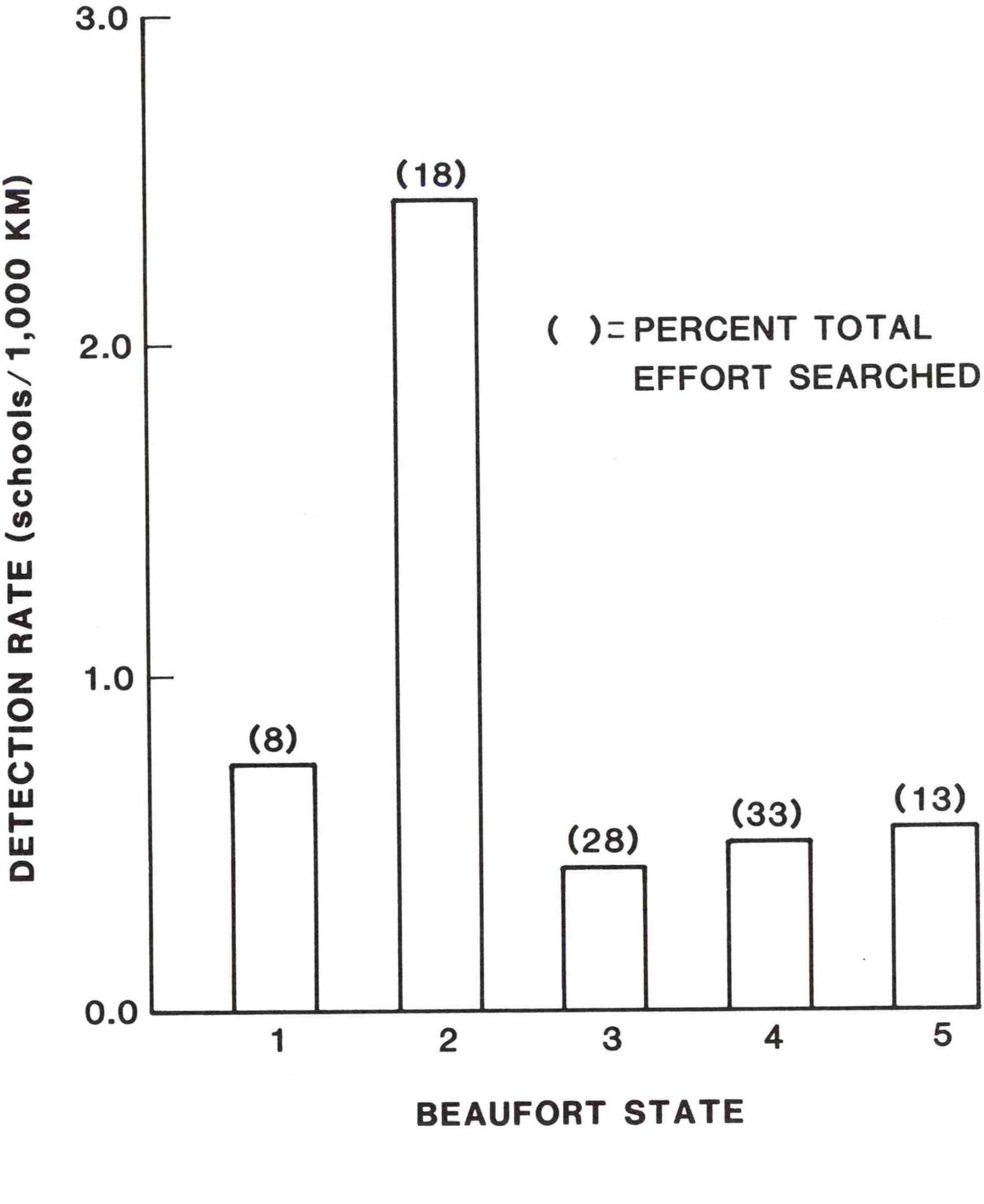


Figure 24. School detection rates of schools on the trackline by Beaufort states. Data are from the 1977 and 1979 aerial surveys in the inshore area.

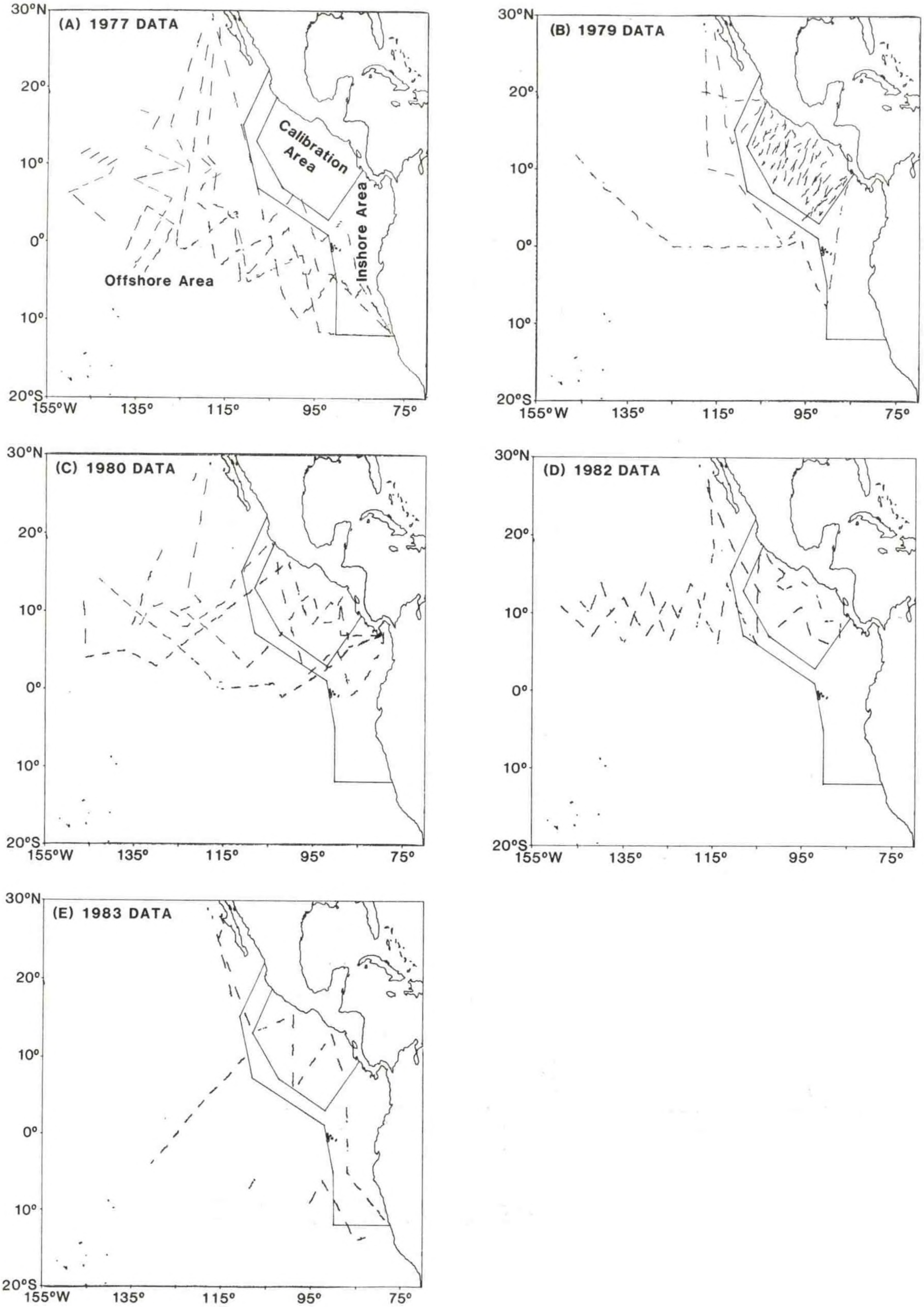


Figure 25. Tracklines for the ship surveys by year: (A) 1977, (B) 1979, (C) 1980, (D) 1982, and (E) 1983.

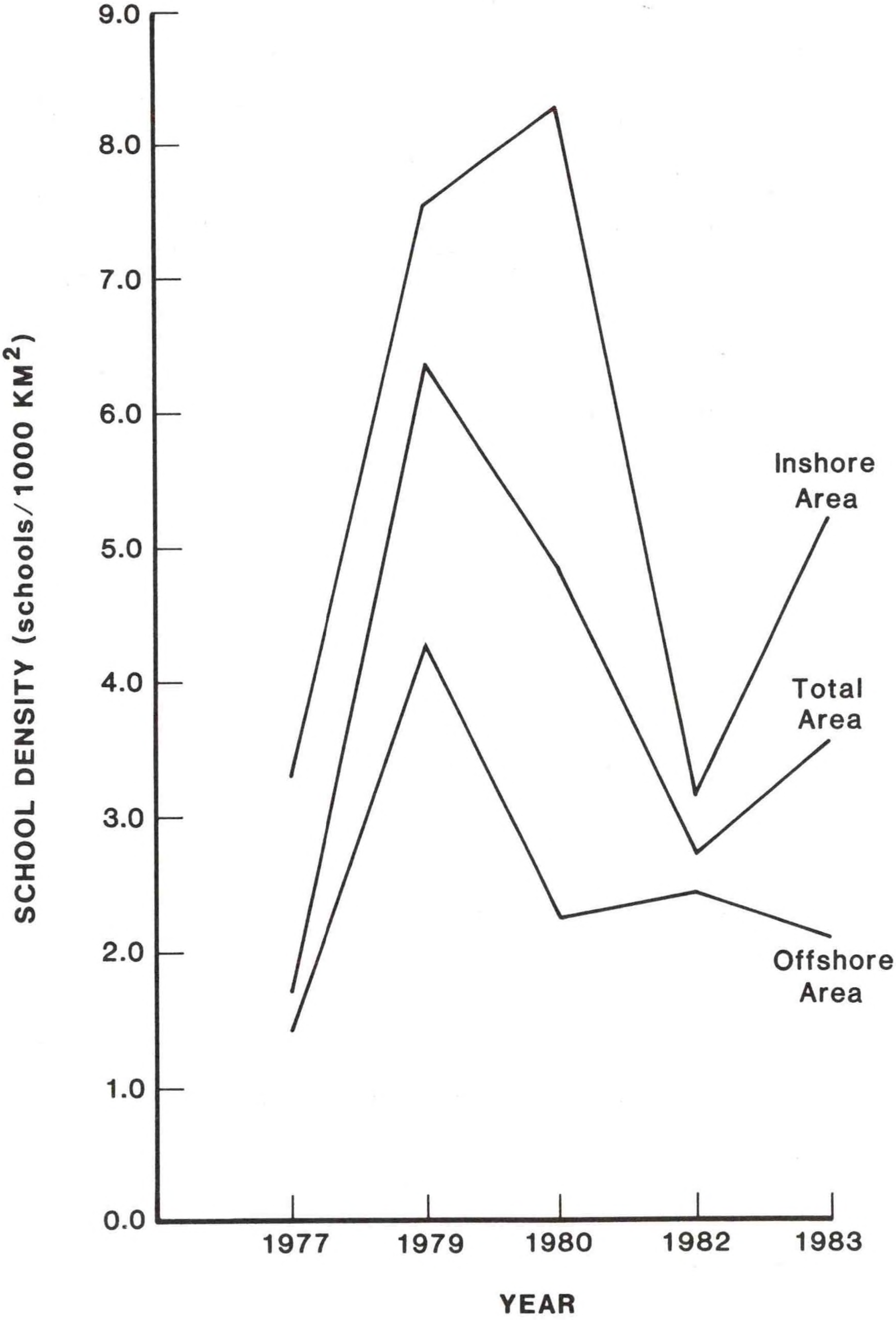


Figure 26. Relative school density estimates by year and area. Data are from the 1977-83 ship surveys.

APPENDIX 1

Example of Computing Shipboard Density Estimates

Calculating density estimates using ship data is somewhat complex, therefore, the following example using 2.1-km truncated detection rates is provided. See Table 5 for results of these calculations.

Let $\hat{D}$= estimated density, T= 79-80 Townsend Cromwell, W= 77 Townsend Cromwell, J= 79-83 Jordan, S= 77 Jordan, O= offshore area, M= calibration area, C= calm sea states, R= rough sea states, P= proportion of schools/1000 km (detection rates), B= PBY and L= km searched in offshore area.

Using equation 5:

$$\hat{D}_{JOC} = \left(\frac{\hat{D}_{BMC}}{P_{JMC}}\right) * P_{JOC}$$

$$\hat{D}_{JOR} = \left(\frac{\hat{D}_{BMR}}{P_{JMR}}\right) * P_{JOR}$$

$$\hat{D}_{TOC} = \left(\frac{\hat{D}_{BMC}}{P_{TMC}}\right) * P_{TOC}$$

$$\hat{D}_{TOR} = \left(\frac{\hat{D}_{BMR}}{P_{TMR}}\right) * P_{TOR}$$

$$\hat{D}_{SO} = \left(\frac{\hat{D}_{BM}}{P_{SM}}\right) * P_{SO}$$

$$\hat{D}_{WO} = \left(\frac{\hat{D}_{BM}}{P_{WM}}\right) * P_{WO}$$

Each estimate is then combined weighted by the amount of searching effort in the offshore area as:

$$\hat{D}_{O} = \left[\frac{\hat{D}_{JOC} * L_{JOC} + \hat{D}_{JOR} * L_{JOR} + \hat{D}_{TOC} * L_{TOC} + \hat{D}_{TOR} * L_{TOR} + \hat{D}_{SO} * L_{SO} + \hat{D}_{WO} * L_{WO}}{L_{JOC} + L_{JOR} + L_{TOC} + L_{TOR} + L_{SO} + L_{WO}}\right]$$

Calculations using aerial calibration data (Table 2) and ship data truncated at 2.13 km (Table 3) were:

$$\hat{D}_{JOC} = \left(\frac{3.59}{22.45}\right) * 11.24 = 6.80$$

$$\hat{D}_{JOR} = \left(\frac{3.91}{7.77}\right) * 4.47 = 2.25$$

$$\hat{D}_{TOC} = \left(\frac{13.59}{15.18}\right) * 3.30 = 2.95$$

$$\hat{D}_{TOR} = \left(\frac{3.91}{5.99}\right) * 2.62 = 1.71$$

$$\left(\hat{D}_{SO}\right) = \frac{6.13}{14.95} * 3.95 = 1.62$$

$$\left(\hat{D}_{WO}\right) = \frac{6.13}{8.69} * 1.57 = 1.11$$

Using equation 7 and km searched in the offshore area from Table 3:

$$\hat{D}_O = 6.80 * 3827 + 2.25 * 12756 + 2.95 * 303 + 1.71 * 7258 + 1.62 * 15433 + 1.11 * 6991 = 2.16$$

APPENDIX 2

Deletion of Ship Beaufort 5 and Beaufort 4 and 5 Data

Sea conditions during the surveys and during an experiment designed to test sea conditions (Holt 1984) were not similar. Extreme Beaufort states 4 and 5 were not encountered as often during the experiment as they were during the surveys. Therefore I omitted Beaufort 5 and then Beauforts 4 and 5 conditions from the aerial and ship data to allow comparisons with the experimental results. Tables A2-1 through A2-3 present analysis with these data omitted.

Table A2-1. Estimates of school density for 1979 aerial calibration data and 1977 plus 1979 aerial inshore data with Beaufort 5 and with Beaufort 4 and 5 data deleted. Data are stratified by calm (Csea) and rough (Rsea) sea and good (Gsun) and poor (Psun) sun conditions.

Variable	Distance Searched (km)	Number Terms in model	Number Schools Detected (n)	S.E.(n)	$\hat{f}(0)$	S.E.$\hat{f}(0)$	Density ($\hat{D}$) (Schools/ 1000 (km^2)	Var ($\hat{D}$)	S.E. ($\hat{D}$)	C.V. ($\hat{D}$)	Number Flights
Calibration Area											
Beaufort 5 Data Deleted											
All Data	8664	5	55	11.00	2.35	0.276	7.46	2.993	1.730	0.232	10
Csea	2455	9	29	4.56	2.30	0.749	13.59	24.135	4.913	0.362	10
Rsea	6209	3	26	8.51	1.73	0.011	3.62	1.406	1.186	0.327	10
Gsun	3212	6	27	7.78	3.34	0.318	14.04	18.149	4.260	0.303	9
Psun	5452	2	28	6.29	1.14	0.194	2.93	0.680	0.825	0.282	10
Beaufort 4 and 5 Data Deleted											
All Data	5287	6	46	7.72	2.14	0.398	9.31	5.439	2.332	0.251	10
Csea	2455	9	29	4.56	2.30	0.749	13.59	24.135	4.913	0.362	10
Rsea	2833	2	17	5.90	1.73	0.003	5.19	3.246	1.802	0.347	10
Gsun	2336	6	23	7.04	3.22	0.383	15.85	27.098	5.206	0.328	8
Psun	2951	1	23	3.66	0.97	0.091	3.78	0.488	0.698	0.185	10
Inshore Area											
Beaufort 5 Data Deleted											
All Data	29579	6	148	18.61	1.83	0.226	4.58	0.651	0.807	0.176	26
Csea	8920	9	70	9.20	2.16	0.483	8.48	4.832	2.198	0.259	23
Rsea	20659	3	78	14.76	1.63	0.149	3.08	0.418	0.647	0.210	26
Gsun	10370	5	72	12.24	2.05	0.263	7.12	2.298	1.516	0.213	22
Psun	19210	3	76	11.27	1.60	0.151	3.16	0.309	0.556	0.176	24
Csea-Gsun	3026	9	30	9.00	2.55	0.744	12.64	27.980	5.290	0.418	17
Csea-Psun	5894	9	40	5.98	1.84	0.623	6.24	5.341	2.311	0.370	21
Rsea-Gsun	7343	3	42	10.21	1.74	0.182	4.98	1.734	1.317	0.265	21
Rsea-Psun	13316	1	36	9.07	1.25	0.001	1.69	0.181	0.426	0.252	24
Beauforts 4 and 5 Data Deleted											
All Data	18481	6	122	14.86	1.68	0.247	5.55	1.121	1.059	0.191	26
Csea	8920	9	70	9.20	2.16	0.483	8.48	4.832	2.198	0.259	23
Rsea	9561	2	52	10.82	1.38	0.111	3.75	0.701	0.837	0.223	26
Gsun	6146	4	54	10.00	1.83	0.240	8.04	3.328	1.824	0.227	20
Psun	12335	3	68	8.69	1.62	0.157	4.47	0.513	0.716	0.160	24
Csea-Gsun	3026	9	30	9.00	2.55	0.744	12.64	27.980	5.290	0.418	17
Csea-Psun	5894	9	40	5.98	1.84	0.623	6.24	5.341	2.311	0.370	21
Rsea-Gsun	3120	2	24	6.93	1.24	0.180	4.77	2.376	1.541	0.323	18
Rsea-Psun	6441	1	28	6.22	1.26	0.001	2.74	0.370	0.608	0.222	24

Table A2-2. Detection rates for ship data stratified by year, vessel (DSJ = Jordan and TC = Cromwell), and calm (Csea) and rough (Rsea) sea conditions (with Beaufort 5 and with Beaufort 4 and 5 data deleted) for truncation distances of 2.13 and 7.40 km in the calibration and offshore areas.

				7.4 km Perpendicular Distance				2.1 km Perpendicular Distance				
Data Source	Variable	Distance Searched (km)	Percent km Searched	Number Schools Detected	Percent All Schools Detected	Detection Rate (Schools/ 1000 km)	S.E. (Detection Rate)	Number Schools Detected	Percent Schools Detected	Detection Rate (Schools/ 1000 km	S.E. Detection Rate	Number Days Searched
Calibration Area Beaufort 5 Data Deleted												
79-83 Both	All Data	14891	100.0	282	100.0	18.94	1.71	175	100.0	11.75	1.40	103
79-83 Both	Csea	5681	38.2	161	57.1	28.34	3.28	98	56.0	17.25	2.66	60
79-83 Both	Rsea	9210	61.8	121	42.9	13.14	1.46	77	44.0	8.36	1.18	83
79-83 DSJ	All Data	9822	100.0	203	100.0	20.67	2.47	131	100.0	13.34	2.05	64
79-83 DSJ	Csea	4149	42.2	122	60.1	29.41	4.46	77	58.8	18.56	3.67	38
79-83 DSJ	Rsea	5673	57.8	81	39.9	14.28	2.03	54	41.2	9.52	1.56	50
79-83 TC	All Data	5069	100.0	79	100.0	15.58	1.73	44	100.0	8.68	1.29	39
79-83 TC	Csea	1532	30.2	39	49.4	25.46	4.11	21	47.7	13.71	2.89	22
79-83 TC	Rsea	3537	69.8	40	50.6	11.31	2.01	23	52.3	6.50	1.78	33
79 Both	All Data	8908	100.0	179	100.0	20.09	2.23	113	100.0	12.69	1.62	58
79 Both	Csea	3901	43.8	127	70.9	32.56	3.47	78	69.0	20.00	2.51	39
79 Both	Rsea	5007	56.2	52	29.1	10.39	1.68	35	31.0	6.99	1.51	43
79 DSJ	All Data	4826	100.0	117	100.0	24.24	3.86	76	100.0	15.75	2.77	27
79 DSJ	Csea	2583	53.5	94	80.3	36.39	4.85	58	76.3	22.45	3.63	20
79 DSJ	Rsea	2243	46.5	23	19.7	10.25	2.39	18	23.7	8.02	2.13	17
79 TC	All Data	4082	100.0	62	100.0	15.19	1.95	37	100.0	9.06	1.49	31
79 TC	Csea	1318	32.3	33	53.2	25.04	4.65	20	54.1	15.18	3.21	19
79 TC	Rsea	2764	67.7	29	46.8	10.49	2.37	17	45.9	6.15	2.12	26
80 Both	All Data	2479	100.0	52	100.0	20.98	5.60	36	100.0	14.52	5.51	19
80 Both	Csea	774	31.2	18	34.6	23.26	13.01	11	30.6	14.21	13.00	10
80 Both	Rsea	1705	68.8	34	65.4	19.94	3.87	25	69.4	14.66	3.53	15
80 DSJ	All Data	1491	100.0	35	100.0	23.47	9.22	29	100.0	19.44	9.04	11
80 DSJ	Csea	560	37.5	12	34.3	21.44	18.44	10	34.5	17.86	18.47	7
80 DSJ	Rsea	932	62.5	23	65.7	24.69	6.24	19	65.5	20.39	5.31	8
80 TC	All Data	987	100.0	17	100.0	17.22	3.97	7	100.0	7.09	2.54	8
80 TC	Csea	214	21.7	6	35.3	28.03	8.27	1	14.3	4.67	3.19	3
80 TC	Rsea	773	78.3	11	64.7	14.22	3.54	6	85.7	7.76	3.19	7
82 DSJ	All Data	2297	100.0	28	100.0	12.19	2.62	14	100.0	6.09	1.88	16
82 DSJ	Csea	606	26.4	4	14.3	6.61	3.13	2	14.3	3.30	1.68	5
82 DSJ	Rsea	1692	73.6	24	85.7	14.19	3.85	12	85.7	7.09	2.24	15
83 DSJ	All Data	1207	100.0	23	100.0	19.06	3.80	12	100.0	9.94	2.48	10
83 DSJ	Csea	401	33.2	12	52.2	29.96	11.28	7	58.3	17.48	6.64	6
83 DSJ	Rsea	806	66.8	11	47.8	13.64	5.19	5	41.7	6.20	3.18	10

Table A2-2 (continued)

Data Source	Variable	Distance Searched (km)	Percent km Searched	7.4 km Perpendicular Distance: Number Schools Detected	Percent All Schools Detected	Detection Rate (Schools/ 1000 km)	S.E. (Detection Rate)	2.1 km Perpendicular Distance: Number Schools Detected	Percent Schools Detected	Detection Rate (Schools/ 1000 km)	S.E. (Detection Rate)	Number Days Searched
Beauforts 4 and 5 Data Deleted												
79-83 Both	All Data	10699	100.0	239	100.0	22.34	2.12	147	100.0	13.74	1.77	87
79-83 Both	Csea	5681	53.1	161	67.4	28.34	3.28	98	66.7	17.25	2.66	60
79-83 Both	Rsea	5018	46.9	78	32.6	15.54	2.15	49	33.3	9.76	1.77	67
79-83 DSJ	All Data	7242	100.0	172	100.0	23.75	3.02	112	100.0	15.47	2.53	56
79-83 DSJ	Csea	4149	57.3	122	70.9	29.41	4.46	77	68.8	18.56	3.67	38
79-83 DSJ	Rsea	3093	42.7	50	29.1	16.17	2.94	35	31.3	11.32	2.32	42
79-83 TC	All Data	3457	100.0	67	100.0	19.38	2.09	35	100.0	10.12	1.62	31
79-83 TC	Csea	1532	44.3	39	58.2	25.46	4.11	21	60.0	13.71	2.89	22
79-83 TC	Rsea	1925	55.7	28	41.8	14.54	3.06	14	40.0	7.27	2.71	25
79 Both	All Data	6940	100.0	167	100.0	24.06	2.48	104	100.0	14.99	1.86	50
79 Both	Csea	3901	56.2	127	76.0	32.56	3.47	78	75.0	20.00	2.51	39
79 Both	Rsea	3039	43.8	40	24.0	13.16	2.36	26	25.0	8.56	2.12	35
79 DSJ	All Data	4085	100.0	112	100.0	27.42	4.08	72	100.0	17.62	2.98	25
79 DSJ	Csea	2583	63.2	94	83.9	36.39	4.85	58	80.6	22.45	3.63	20
79 DSJ	Rsea	1502	36.8	18	16.1	11.98	3.00	14	19.4	9.32	2.64	15
79 TC	All Data	2855	100.0	55	100.0	19.27	2.28	32	100.0	11.21	1.84	25
79 TC	Csea	1318	46.2	33	60.0	25.04	4.65	20	62.5	15.18	3.21	19
79 TC	Rsea	1537	53.8	22	40.0	14.32	3.61	12	37.5	7.81	3.28	20
80 Both	All Data	1644	100.0	33	100.0	20.07	7.17	22	100.0	13.38	7.16	16
80 Both	Csea	774	47.1	18	54.5	23.26	13.01	11	50.0	14.21	13.00	10
80 Both	Rsea	871	52.9	15	45.5	17.23	4.46	11	50.0	12.63	4.57	12
80 DSJ	All Data	1042	100.0	21	100.0	20.16	11.19	19	100.0	18.24	11.20	10
80 DSJ	Csea	560	53.7	12	57.1	21.44	18.44	10	52.6	17.86	18.47	7
80 DSJ	Rsea	482	46.3	9	42.9	18.68	6.90	9	47.4	18.68	6.90	7
80 TC	All Data	603	100.0	12	100.0	19.91	5.57	3	100.0	4.98	2.67	6
80 TC	Csea	214	35.5	6	50.0	28.03	8.27	1	33.3	4.67	3.19	3
80 TC	Rsea	389	64.5	6	50.0	15.44	5.71	2	66.7	5.15	3.88	5
82 DSJ	All Data	1379	100.0	19	100.0	13.78	3.47	11	100.0	7.98	2.59	12
82 DSJ	Csea	606	43.9	4	21.1	6.61	3.13	2	18.2	3.30	1.68	5
82 DSJ	Rsea	773	56.1	15	78.9	19.39	5.84	9	81.8	11.64	3.23	11
83 DSJ	All Data	736	100.0	20	100.0	27.18	8.65	10	100.0	13.59	7.13	9
83 DSJ	Csea	401	54.5	12	60.0	29.96	11.28	7	70.0	17.48	6.64	6
83 DSJ	Rsea	335	45.5	8	40.0	23.85	12.94	3	30.0	8.94	10.25	9

Table A2-2 (continued)

Data Source	Variable	Distance Searched (km)	Percent km Searched	7.4 km Perpendicular Distance: Number Schools Detected	Percent All Schools Detected	Detection Rate (Schools/1000 km)	S.E. (Detection Rate)	2.1 km Perpendicular Distance: Number Schools Detected	Percent Schools Detected	Detection Rate Schools/1000 km)	S.E. Detection Rate	Number Days Searched
Offshore Area Beaufort 5 Data Deleted												
79-83 Both	All Data	20889	100.0	160	100.0	7.66	1.14	111	100.0	5.31	0.83	132
79-83 Both	Csea	4129	19.8	68	42.5	16.47	3.17	44	39.6	10.66	2.30	58
79-83 Both	Rsea	16760	80.2	92	57.5	5.49	0.72	67	60.4	4.00	0.60	123
79-83 DSJ	All Data	13872	100.0	138	100.0	9.95	1.58	91	100.0	6.56	1.16	93
79-83 DSJ	Csea	3827	27.6	66	47.8	17.25	3.47	43	47.3	11.24	2.53	51
79-83 DSJ	Rsea	10045	72.4	72	52.2	7.17	1.00	48	52.7	4.78	0.84	84
79-83 TC	All Data	7017	100.0	22	100.0	3.14	0.75	20	100.0	2.85	0.69	39
79-83 TC	Csea	303	4.3	2	9.1	6.61	4.34	1	5.0	3.30	2.17	7
79-83 TC	Rsea	6714	95.7	20	90.9	2.98	0.76	19	95.0	2.83	0.74	39
79 Both	All Data	6240	100.0	60	100.0	9.62	3.63	45	100.0	7.21	2.60	34
79 Both	Csea	1872	30.0	43	71.7	22.97	7.33	31	68.9	16.56	5.02	20
79 Both	Rsea	4368	70.0	17	28.3	3.89	1.75	14	31.1	3.20	1.70	30
79 DSJ	All Data	3319	100.0	51	100.0	15.37	6.36	37	100.0	11.15	4.53	19
79 DSJ	Csea	1610	48.5	41	80.4	25.46	8.96	30	81.1	18.63	6.10	15
79 DSJ	Rsea	1708	51.5	10	19.6	5.85	3.63	7	18.9	4.10	3.55	15
80 Both	All Data	6684	100.0	35	100.0	5.24	1.02	28	100.0	4.19	0.92	42
80 Both	Csea	485	7.3	5	14.3	10.30	4.95	4	14.3	8.24	4.94	8
80 Both	Rsea	6199	92.7	30	85.7	4.84	0.98	24	85.7	3.87	0.87	40
80 DSJ	All Data	2589	100.0	22	100.0	8.50	1.90	16	100.0	6.18	1.81	18
80 DSJ	Csea	444	17.2	5	22.7	11.25	5.95	4	25.0	9.00	6.00	6
80 DSJ	Rsea	2144	82.8	17	77.3	7.93	1.91	12	75.0	5.60	1.75	16
82 DSJ	All Data	5393	100.0	50	100.0	9.27	1.39	26	100.0	4.82	1.00	36
82 DSJ	Csea	1562	29.0	18	36.0	11.53	2.51	7	26.9	4.48	1.93	23
82 DSJ	Rsea	3832	71.0	32	64.0	8.35	1.51	19	73.1	4.96	0.99	33
83 DSJ	All Data	2571	100.0	15	100.0	5.83	1.38	12	100.0	4.67	1.06	20
83 DSJ	Csea	210	8.2	2	13.3	9.51	3.15	2	16.7	9.51	3.15	7
83 DSJ	Rsea	2361	91.8	13	86.7	5.51	1.47	10	83.3	4.24	1.18	20

Table A2-2 (continued)

Data Source	Variable	Distance Searched (km)	Percent km Searched	7.4 km Perpendicular Distance: Number Schools Detected	Percent All Schools Detected	Detection Rate (Schools/ 1000 km)	S.E. Detection Rate	2.1 km Perpendicular Distance: Number Schools Detected	Percent All Schools Detected	Detection Rate (Schools/ 1000 km	S.E. (Detection Rate	Number Days Searched
Offshore Area Beauforts 4 and 5 Data Deleted												
79-83 Both	All Data	13135	100.0	134	100.0	10.20	1.56	90	100.0	6.85	1.17	106
79-83 Both	Csea	4129	31.4	68	50.7	16.47	3.17	44	48.9	10.66	2.30	58
79-83 Both	Rsea	9006	68.6	66	49.3	7.33	1.11	46	51.1	5.11	0.95	97
79-83 DSJ	All Data	9656	100.0	119	100.0	12.32	2.04	76	100.0	7.87	1.54	78
79-83 DSJ	Csea	3827	39.6	66	55.5	17.25	3.47	43	56.6	11.24	2.53	51
79-83 DSJ	Rsea	5829	60.4	53	44.5	9.09	1.51	33	43.4	5.66	1.30	69
79-83 TC	All Data	3479	100.0	15	100.0	4.31	1.07	14	100.0	4.02	1.02	28
79-83 TC	Csea	303	8.7	2	13.3	6.61	4.34	1	7.1	3.30	2.17	7
79-83 TC	Rsea	3177	91.3	13	86.7	4.09	1.13	13	92.9	4.09	1.13	28
79 Both	All Data	4544	100.0	58	100.0	12.76	4.48	43	100.0	9.46	3.20	29
79 Both	Csea	1872	41.2	43	74.1	22.97	7.33	31	72.1	16.56	5.02	20
79 Both	Rsea	2672	58.8	15	25.9	5.61	2.53	12	27.9	4.49	2.35	25
79 DSJ	All Data	2666	100.0	50	100.0	18.75	7.07	36	100.0	13.50	5.05	18
79 DSJ	Csea	1610	60.4	41	82.0	25.46	8.96	30	83.3	18.63	6.10	15
79 DSJ	Rsea	1056	39.6	9	18.0	8.52	4.99	6	16.7	5.68	4.66	14
80 Both	All Data	3432	100.0	24	100.0	6.99	1.52	19	100.0	5.54	1.37	30
80 Both	Csea	485	14.1	5	20.8	10.30	4.95	4	21.1	8.24	4.94	8
80 Both	Rsea	2946	85.9	19	79.2	6.45	1.53	15	78.9	5.09	1.32	28
80 DSJ	All Data	1830	100.0	17	100.0	9.29	2.67	12	100.0	6.56	2.43	13
80 DSJ	Csea	444	24.3	5	29.4	11.25	5.95	4	33.3	9.00	6.00	6
80 DSJ	Rsea	1385	75.7	12	70.6	8.66	2.92	8	66.7	5.77	2.43	11
82 DSJ	All Data	3744	100.0	43	100.0	11.48	1.81	21	100.0	5.61	1.50	32
82 DSJ	Csea	1562	41.7	18	41.9	11.53	2.51	7	33.3	4.48	1.93	23
82 DSJ	Rsea	2183	58.3	25	58.1	11.45	2.24	14	66.7	6.41	1.76	29
83 DSJ	All Data	1415	100.0	9	100.0	6.36	2.30	7	100.0	4.95	2.14	15
83 DSJ	Csea	210	14.8	2	22.2	9.51	3.15	2	28.6	9.51	3.15	7
83 DSJ	Rsea	1205	85.2	7	77.8	5.81	2.52	5	71.4	4.15	2.39	15

Table A2-3. Relative density estimates for all ship data and stratified by year, vessel (DSJ = Jordan and TC = Cromwell), and calm (Csea) and rough (Rsea) sea conditions with Beaufort 5 and Beaufort 4 and 5 data deleted in the calibration and offshore areas.

Data Source	Variable	Number Terms in Model	Number Schools Detected (n)	S.E.(n)	$\hat{f}(0)$	S.E.$\hat{f}(0)$	Density ($\hat{D}$) (Schools/1000 km^2)	Var ($\hat{D}$)	S.E. ($\hat{D}$)	C.V. ($\hat{D}$)	Number Days Searched
Beaufort 5 Data Deleted Calibration Area											
79 Both	All Data	6	146	14.44	0.66	0.109	5.41	1.084	1.041	0.193	58
79 DSJ	All Data	7	100	13.38	0.70	0.156	7.25	3.553	1.885	0.260	27
79 DSJ	Csea	5	79	9.38	0.58	0.129	8.87	5.001	2.236	0.252	20
79 DSJ	Rsea	7	19	4.78	1.11	0.380	4.70	3.989	1.997	0.425	17
79 TC	All Data	7	47	6.08	0.61	0.218	3.51	1.782	1.335	0.380	31
79 TC	Csea	1	26	4.23	0.41	0.068	4.04	0.883	0.940	0.232	19
79 TC	Rsea	7	23	5.87	0.77	0.325	3.20	2.497	1.580	0.493	26
Offshore Area											
79-83 DSJ	Csea	6	54	9.66	0.78	0.185	5.50	2.673	1.635	0.297	51
79-83 DSJ	Rsea	5	61	8.41	0.86	0.153	2.61	0.345	0.588	0.225	84
79-83 TC	All Data	7	22	4.83	1.04	0.366	1.63	0.457	0.676	0.415	39
77 DSJ	All Data	6	81	12.26	0.69	0.145	1.81	0.220	0.469	0.259	76
77 TC	All Data	2	13	3.90	0.83	0.034	0.77	0.055	0.234	0.303	32
79 Both	All Data	5	54	16.21	0.80	0.167	3.46	1.602	1.266	0.366	34
80 Both	All Data	7	30	6.18	1.31	0.308	2.94	0.845	0.919	0.313	42
82 DSJ	All Data	7	37	5.42	0.48	0.225	1.65	0.654	0.809	0.491	36
83 DSJ	All Data	5	10	2.73	1.71	0.121	3.33	0.880	0.938	0.282	20
Beauforts 4 and 5 Data Deleted Calibration Area											
79 Both	All Data	7	138	12.89	0.60	0.127	5.97	1.905	1.380	0.231	50
79 DSJ	All Data	7	94	12.18	0.66	0.158	7.59	4.273	2.067	0.272	25
79 DSJ	Csea	5	79	9.38	0.58	0.129	8.87	5.001	2.236	0.252	20
79 DSJ	Rsea	7	17	3.96	0.86	0.390	4.87	6.157	2.481	0.510	15
79 TC	All Data	6	42	5.26	0.60	0.197	4.41	2.405	1.551	0.351	25
79 TC	Csea	1	26	4.23	0.41	0.068	4.04	0.883	0.940	0.232	19
79 TC	Rsea	7	15	5.04	0.71	0.374	3.46	4.687	2.165	0.625	20
Offshore Area											
79-83 DSJ	All Data	5	97	14.85	0.74	0.120	3.72	0.687	0.829	0.223	78
79-83 DSJ	Csea	6	54	9.66	0.78	0.185	5.50	2.673	1.635	0.297	51
79-83 DSJ	Rsea	4	44	7.58	0.72	0.146	2.72	0.523	0.723	0.266	69
79-83 TC	All Data	6	14	3.55	0.97	0.365	1.95	0.785	0.886	0.454	28
77 DSJ	All Data	6	81	12.26	0.69	0.145	1.81	0.220	0.469	0.259	76
77 TC	All Data	2	13	3.90	0.83	0.034	0.77	0.055	0.234	0.303	32
79 Both	All Data	5	52	14.56	0.75	0.169	4.29	2.378	1.542	0.359	29
80 Both	All Data	7	21	4.71	1.37	0.373	4.19	2.186	1.478	0.353	30
82 DSJ	All Data	1	29	5.62	0.34	0.070	1.32	0.139	0.372	0.283	32
83 DSJ	All Data	1	5	3.03	0.76	0.001	1.34	0.662	0.814	0.606	15

APPENDIX 3

Correcting Density Estimates for Poor Sighting Conditions.

An observed (calculated) density estimate of dolphins in an area may be biased by adverse effects of environmental or operational factors. Suppose there are two levels of a factor and one has no affect while the other has an impact, either negative or positive, on the true density, then the computed density ($\hat{D}_c$) is a weighted average of the two levels:

$$\hat{D}_c = P_p \hat{D}_p + (1-P_p) \hat{D}_g \qquad (1)$$

where P_p is the proportion of total effort during the unfavorable (poor) condition, $\hat{D}_p$ is the (unknown) density which would be computed using only data obtained during the poor condition, and $\hat{D}_g$ is the (unknown) density which would be computed using data obtained during the favorable (good) condition. However, $\hat{D}_g$ is the true density ($\hat{D}_t$). From equation 1

$$\hat{D}_g = \frac{\hat{D}_c - P_p \hat{D}_p}{1-P_p} \qquad (2)$$

Although $\hat{D}_g$ and $\hat{D}_p$ are both unknown, the ratio (K) of the two densities may be obtained from independent experimental data and assuming the ratio is constant

$$K = \frac{\hat{D}_p'}{\hat{D}_g'} = \frac{\hat{D}_p}{\hat{D}_g} \qquad (3)$$

where $\hat{D}_p'$ and $\hat{D}_g'$ are density estimates obtained from experimental data. Solving for $\hat{D}_p$ and substituting in equation 3 gives

$$\hat{D}_g = \frac{\hat{D}_c - KP_p \hat{D}_g}{1-P_p}$$

and

$$\hat{D}_t = \frac{\hat{D}_c}{1-P_p + KP_p} \qquad (4)$$

The corrected density (equation 4) was derived without considering effect of other factors. If a corrected density is computed within levels of some other factor, then equation 4 provides the corrected density for the ith level of the other factor ($\hat{D}_i$) if the observed computed density ($\hat{D}_{ci}$) for that level is used in place of $\hat{D}_c$ and P_{pi} is substituted for P_p in equation 4. This assumes that equation 4 is true for all levels of the other factor (i.e. that there is no interaction between the two factors).

An estimate of the variance of $\hat{D}$ (equation 4) was obtained using the first order Taylor approximation method where $\hat{D}_c$ and K are variables and P_p is a constant. Therefore,

$$\hat{V}ar(\hat{D}) = \left[\frac{1}{(1-P_p+KP_p)^2}\right]^2 \hat{v}ar\ (\hat{D}_c) + \left[\frac{\hat{D}_c}{(1-P_p+KP_p)^2}\right]^2 \hat{v}ar\ (1-P_p+KP_p) \qquad (5)$$

where $\hat{V}ar\ (\hat{D}_c)$ and $\hat{V}ar(1-P_p+KP_p)$ are the indicated estimated variances. Since P_p is constant,

$$Var(1-P_p+KP_p) = P_p^{\ 2}\ var(K) = P_p^{\ 2}\ var\left(\frac{\hat{D}'_p}{\hat{D}'_g}\right) = P_p^{\ 2}\left[\left(\frac{1}{\hat{D}'_g}\right)^2 var(\hat{D}'_p) + \left(\frac{\hat{D}'_p}{\hat{D}'_g}\right)^2 var(\hat{D}'_g)\right] \qquad (6)$$

Substituting equation 6 into equation 5

$$Var(\hat{D}) = \left[\frac{1}{(1-P_p+KP_p)^2}\right] var(\hat{D}_c) + \left[\frac{P_p\hat{D}_c}{(1-P_p+KP_p)^2\hat{D}'_g}\right]^2 \left[var(\hat{D}'_g) + \left(\frac{\hat{D}'_P}{\hat{D}'_g}\right)^2 var(\hat{D}'_g)\right]$$

Again note that, if $\hat{D}$ is computed for separate categories of more than one factor, then $\hat{D}_c$ and $\hat{P}_p$ are replaced by $\hat{D}_{ci}$ and $\hat{P}_{pi}$, respectively.